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SNOW AVALANCHE HAZARD IN KANANASKIS COUNTRY, ALBERTA: THE DEVELOPMENT OF A TIME-LAPSE SLOPE MONITORING SYSTEM

by

© Fes Alexander de Scally

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

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.....

Supervisor

.....

.....

Walter Moser

Date ..... 20 July 84 .....

Dedication

This thesis is dedicated to the memory of my dear grandparents, Mamma Piela and Pappa de Scally.

Abstract

The objectives of this research were to determine whether time-lapse photography would provide useful information on snow avalanche activity over an entire winter, and secondly, to use such information as an aid in determining the types and causes of avalanches over the winter. The lack of a continuous avalanche record has been a major weakness in most studies of this type. Two large avalanche paths in Kananaskis Country, Alberta were monitored continuously during the winter of 1982-83 using such photography systems. To accomplish the second objective, detailed weather and snowpack data were also collected during visits to the study areas.

The time-lapse photography systems operated continuously and successfully all winter, and provided information on the frequency, size, type and distance of travel of avalanches, and on accompanying weather conditions. The film records indicated that both paths avalanche actively during the winter. Earlier dendrochronological methods employed there had only been able to determine the frequency of large, spectacular avalanches, but not of smaller ones still quite capable of causing injury and death to winter recreationists. Wet snow and dry snow soft slab avalanches were dominant in 1982-83, with wet snow avalanches especially numerous in the spring.

Snowpack data indicated that the development of snowpack structure in both study areas in 1982-83 closely followed the general seasonal evolution of a snowcover in a cold subhumid continental climate. Most notable were the production of weak depth hoar grains early in the winter, and the development of complex upper-snowpack stratigraphies in the spring, which contained numerous weak layer interfaces. The patterns of snowpack instability closely followed this seasonal evolution of the snowcover. The examination of avalanche failure planes in the snowpack indicated that these in turn reflected quite closely the sources of instability. Most failures occurred at the interfaces of distinct and cohesive layers, rather than within layers themselves.

Comparison of the avalanche records with weather data revealed that short-term weather events triggered all of the recorded avalanches. Snowpack instabilities alone were insufficient to cause avalanches. Snowfall and rises in air temperature triggered most releases, although a combination of the two was responsible for many avalanches. Wind was an additional triggering mechanism, increasing new snow deposition on lee

slopes and packing that new snow into slabs.

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1. INTRODUCTION

1.1 Background and Objectives

Snow avalanche research has increased in diverse parts of the world for one basic reason: escalating human activity in mountainous areas has resulted in increasing contact with avalanches. Thus while avalanches are in themselves a mountain process, albeit a catastrophic and powerful one, avalanche *hazard* has developed as people and property have come into proximity with avalanche areas (Mellor, 1968, p.3). In North America research has primarily been the outcome of the proliferation of activities such as mining, transportation and recreation in mountain regions. Yet, as Price (1981, p.155) notes:

> "It is ironic that despite our greater scientific understanding of avalanches and our considerable investment in their prediction and prevention, the number of accidents continues to increase, primarily because more and more people, especially recreationists, go to the mountains during the winter."

Kananaskis Country is a large outdoor recreation development in southwestern Alberta, located in the Front Ranges of the Canadian Rocky Mountains. The physical relief of the area is significant with peak elevations in the order of 2700 to 3000 metres. Slopes are generally steep and this, associated with substantial areas above timberline which robs the slopes of the stabilizing influence of forest, results in considerable avalanche activity. However, research on avalanche phenomena has been limited in Kananaskis Country, primarily as a result of the relatively unintensive use of the area compared to the National Parks further west. It has also been relatively inaccessible until recently, when the Government of Alberta decided to open the area to outdoor recreation activities (Alberta Recreation and Parks, 1977). This decision, manifested in the Kananaskis Country recreation concept (Alberta Recreation and Parks, 1977) as well as the establishment of Kananaskis Provincial Park (Alberta Recreation and Parks, 1978) now ensures escalating use of the area for winter recreation activities. Concomitant with this increase in use will be an increase in the number of recreationists exposed to avalanches. The number of small but nevertheless lethal avalanches can also be expected to rise in Kananaskis Country as skiers themselves trigger unstable slopes into motion; this was illustrated during the winter of 1982-83 by a helicopter skier fatality.

Most avalanche research is handicapped by the capricious nature of avalanches themselves. Such unpredictability results from the complex combinations of terrain configuration, weather and snowpack conditions that cause the sudden release and movement of snow masses down a mountainside. The documentation of avalanche occurrence is an especially significant weakness in most studies (LaChapelle, 1977b; pers. comm., 1984), since it is often impossible for avalanche workers to continuously monitor avalanche-prone slopes. Thus, records of avalanche activity have often been based on post-event observations of questionable accuracy.

Understanding the causes of avalanches is a critical facet of avalanche research, even though these are often complex, as noted above. Any avalanche management approach, whether in the form of artificial terrain or snowcover modification, land-use zoning and planning, or public warning and education, requires a sound understanding of why avalanches occur. Obtaining such knowledge is especially important in mountain regions such as Kananaskis Country, where increasing numbers of people will make their way into avalanche terrain. Although research findings from other areas have some general applicability in the Kananaskis, the physiographic and climatic characteristics unique to each mountain region make such comparisons difficult.

The objectives of this research were two-fold. The first was to develop and test a time-lapse photography system for continuously monitoring avalanche paths. Such a system would be very useful for gathering information on avalanche activity, especially in remote and difficult to access areas where regular human observations are impractical or impossible.

The second objective was to monitor the types and determine the causes of avalanches in two areas in Kananaskis Country during the 1982-83 winter season.

1.2 Literature Review: Avalanche Hazard Research

Snow avalanches have long represented one of the most active areas of applied glaciology (LaChapelle, 1977b). Their study draws on the resources of reseachers from numerous disciplines. As a result, the treatment of snow avalanches in the literature is extensive but widely scattered in scientific and engineering journals, government reports and research papers (LaChapelle, 1977b).

Few comprehensive textbooks are available on the subject, with the exception of Seligman's (1936) dated but classic monograph, Fraser's (1978) introductory text, Mellor's (1968) extensive treatment of the subject, and Perla and Martinelli's (1976) excellent practical manual of avalanche hazard evaluation and control.

Current research into avalanche hazards generally fits into the following categories: avalanche hazard mapping and zoning, artificial release of avalanches, the dynamics of moving avalanches, and the causes of avalanche hazard. The latter field concerns itself with the study of snow behaviour (including its thermodynamic and mechanical properties), weather and terrain in an attempt to understand the complex causes of snowpack instability and the triggering mechanisms necessary for avalanche release. It forms the basis for what is in essence a fifth avenue of endeavour in avalanche research; the evaluation and forecasting of avalanche hazard.

Avalanche mapping and zoning has received particular attention in the European Alps, where a high population density is responsible for pressure to develop in areas subject to avalanche hazard (e.g. Frutiger, 1970; 1977; Oppliger, 1975; de Crécy, 1980; Hestnes and Lied, 1980). Much emphasis has also been placed on the legal bases of avalanche zoning and land-use regulation (Frutiger, 1970; 1980; de Crécy, 1980).

In North America hazard mapping and zoning is primarily restricted to specific construction developments and highways (e.g. Ives and Krebs, 1978; Freer and Schaerer, 1980; Mears, 1980b), since mountain areas at present are still relatively undeveloped. Some efforts have focussed on regional mapping of hazard areas (e.g. Ives and Bovis, 1978; Hackett and Santeford, 1980; Ives and Plam, 1980), with much of the emphasis on hazard for the backcountry tourist. Hazard mapping in its present stage of development is hindered by the lack of data on the extent of runout zones, impact pressures and recurrence intervals, as well as by the absence of an adequate topographic base. The analysis of vegetative evidence however, has provided the researcher with some information on the first three parameters (e.g. Potter, 1969; Smith, 1973; Föhn, 1979).

An extensive literature deals with the complex mechanisms of avalanche release (Ballard and McGaw, 1966; Bradley and Bowles, 1967; Brown *et al*, 1972; Lang and Brown, 1973; Johnson, 1980), since some form of catastrophic failure is required for an unstable slope to avalanche. This research has been aided by theoretical studies on the

complex fracture mechanics of snow slabs[1] (Sommerfeld, 1969; Perla and LaChapelle, 1970; McClung, 1981a).

Knowledge of release mechanisms has been of considerable importance in the artificial triggering of avalanches along highways and railroads and at ski areas, where traffic can be diverted from the hazard area while dangerous accumulations of snow are released (see Perla and Martinelli, 1976). The underlying reasoning is to produce the avalanches while they are still of a manageable size. Explosives are most often employed for this purpose, although there is little limitation on the form of mechanical triggering (LaChapelle, 1977b). An extensive literature in itself is available on the most efficient use of explosives to trigger avalanches (e.g. Gardner and Judson, 1967; Mellor, 1973; Everts, 1976; Gubler, 1977; Everts and Laidlaw, 1978; Kobayashi, 1978; Perla, 1978). Some research has also been directed toward alternate methods of triggering (e.g. Mellor, 1968; Martinelli, 1972; LaChapelle, 1977a; 1978).

Research on the dynamics of moving avalanches has received considerable attention because of its challenging theoretical problems and critical practical value in avalanche zoning and in the design of structures capable of withstanding avalanche forces (LaChapelle, 1977b). Although field research is complicated by different modes of avalanche flow and the difficulty of observing actual avalanches, an impressive amount of literature is available (e.g. Schaerer, 1973; 1975; Mears, 1975; Salway, 1978; Buser and Frutiger, 1980; Schaerer and Salway, 1980). The modelling of flow velocities, runout distances and impact pressures by researchers (Martinelli, 1977; Lang *et al*, 1979; Dent and Lang, 1980; Lang and Brown, 1980; Mears, 1980a; Perla *et al*, 1980; Bakkehøi *et al*, 1981; Dent and Lang, 1982) is based primarily on the calculations of Voellmy (1955) and Salm (1966; 1968).

In conjunction with research on the dynamics of moving avalanches, there have been attempts to develop a universal and widely applicable system of avalanche classification. The relative merits of a morphological as opposed to a genetic classification are still under contention, although a true genetic system will probably never be devised because of the complex conditions of avalanche formation (de Quervain, 1975). Most classification systems as a result are based on the physical characteristics of

---

[1]Cohesive slab-like layers of snow that release as a result of catastrophic, brittle failure of the slope along a fracture line.

the avalanche, beginning with attempts by Coaz (1888; see de Quervain, 1975). Most recent classifications (e.g. Fukui, 1966; Perla and Martinelli, 1976; Canadian Avalanche Committee, 1981) are based on the system devised by de Quervain (1958) and later refined by de Quervain *et al* (1973). In the United States a somewhat different reporting system is sometimes employed (Perla and Martinelli, 1976).

Developments in genetic classification systems have been minimal, with the most important work carried out by Akkuratov (1960; in Lossev, 1966). Lossev has elaborated on Akkuratov's efforts, assigning categories of causation to a classification system based on the relative significance of different meteorological and snowpack parameters to avalanche formation.

A readily communicable classification of avalanche size is an integral part of an overall classification system. However, the fact that most natural avalanches are not observed makes accurate determination of size difficult.

Size classifications have been based on dimensional measurements of the fracture line, avalanche path and debris (de Quervain *et al*, 1973), on determinations of avalanche mass and kinetic energy (Shimizu, 1967), on estimates of the volume of transported material (Perla and Martinelli, 1976), and on the simple criterion of whether the avalanche affects only individuals or entire villages (de Quervain, 1975). However, none of these have proven completely satisfactory for avalanche reporting. The reader is referred to McClung and Schaerer (1981) for a review of developments in avalanche size classification.

The Canadian size classification is based on one originally introduced in the United States by M. Atwater and adopted by the Canadian Avalanche Committee (McClung and Schaerer, 1981). The system relies on an estimation of the potential destructive force of an avalanche (Canadian Avalanche Committee, 1981), which to a large extent is determined by the mass and water content of the debris (McClung and Schaerer, 1981). Though subjective, it assigns a readily communicable estimate of size to avalanches.

The fourth field of research - the causes of avalanches - has received the most attention because of the critical need for information upon which to predict avalanches. The most extensive use of this information has been in the evaluation and forecasting of avalanche hazard for the purpose of public warning or initiation of control measures.

Researchers have recognized the role of snow behaviour, weather and terrain configuration in the development of snowpack instability. However, the actual release of an avalanche requires a triggering agent to communicate an extra increment of energy to the unstable snowpack, enough to make it fail (LaChapelle *et al*, 1978). Price (1981, p.159) describes the situation as follows:

> "A mass of snow perched on a mountainside is like a loaded gun: it awaits only the triggering action to set it off. Many potential avalanches never fall because there was no trigger to release them, while relatively stable snow masses may be released because of external disruptions."

Natural triggering is often accomplished by stress changes resulting from gradual metamorphism of the snowcover, weight of new snow or sudden fluctuations in air temperature, collapse of cornices, sluffing of snow from upslope locations, snow falling from trees and earth tremors. Skiers, climbers and explosive blasts are the most common means of artificial triggering, although initiation of avalanches by various other agents such as sonic booms (e.g. Martinelli, 1972; LaChapelle, 1977b) and vibration from snowplows (LaChapelle, 1977b) have been documented. Artificial triggering, whether intentional or not, generally leads to a much higher frequency of avalanches on a given path than would occur if that path were left to avalanche naturally (Perla and Martinelli, 1976).

Research on the causes of avalanches generally employs one of two approaches. The first is of a theoretical nature, although it involves field measurement in addition to laboratory simulation of natural conditions. It is primarily concerned with understanding the complex behaviour of snow as a material. Because snow can be studied relatively easily in a cold-room environment, a large body of literature is available on theoretical snow behaviour. The effect of weather and terrain configuration on avalanching, on the other hand, has received little theoretical attention because of the impossibility of isolating them for detailed study.

The second approach to research on the causes of avalanches concerns itself with long-term studies in specific mountain regions, usually in response to a need for information on which to base hazard evaluation and forecasting methodologies. In North America this approach has been associated exclusively with transportation corridors and ski developments; studies at Rogers Pass in the Selkirk Mountains of British Columbia

(Schaerer, 1962), the San Juan Mountains of Colorado (Armstrong *et al*, 1974; Armstrong and Ives, 1976; Armstrong and Armstrong, 1981) and the Cascade Mountains of Washington (LaChapelle and Leonard, 1971; LaChapelle *et al*, 1977; LaChapelle *et al*, 1978) are among the most noteworthy ones. In addition, several less ambitious regional projects have been carried out (e.g. Judson, 1964; 1967; Perla, 1970; Martinelli, 1971; Anderson *et al*, 1978; Hutcheon and Lie, 1978; Simms, 1978; Stethem and Hetherington, 1978; Björnsson, 1980). Such long-term research usually attempts to identify the combined effects of snowpack structure, weather and terrain on avalanche activity. As a result, such data are rarely directly applicable to other regions because of the complex interplay of these factors in the formation of instability and avalanches. Nevertheless, general knowledge of the effects of weather and terrain has primarily been obtained from such comprehensive regional projects.

1.2.1 Snow behaviour and avalanches

Snow behaviour research has been hindered by the complex nature of snow. Although high density polar snow conforms to many of the same mechanical laws and properties as other common materials, lower density alpine snow defies many of these physical properties. Consequently it is impossible to predict confidently how it will behave on a mountainside (Perla and Martinelli, 1976).

Regardless of its complex physical properties, the structure of a snowpack is unequivocally a crucial component of its stability. LaChapelle and Armstrong (1976, p.23) note that:

> "The primary significance of this layered structure (of the snowpack) to the avalanche phenomenon is the wide range of strengths associated with the respective layers and the wide variations in interlayer bonding".

Snowpack structure is most significant when avalanches are caused primarily by weak layers that have developed within the snowpack. Incipient structural development can usually be detected well in advance of such 'climax' avalanches (LaChapelle and Armstrong, 1976). Catastrophic failure of the snowpack occurs "... at the culmination of slow load build-up or gradual adverse metamorphism in the snow" (Mellor, 1968, p.24). In such cases changing stability conditions allow sufficient time for pit digging and for

instrument studies of changing snow properties (LaChapelle, 1966). Adverse changes in snowpack structure are especially critical for instability development in climates characterized by low snowfalls and cold temperatures. However, the triggering of latent instability in the snowcover is often conditional on weather events (LaChapelle, 1970).

Snow behaviour research has focussed on the complex thermodynamic (see Palm and Tveitereid, 1979) and mechanical properties of snow. Unlike most other materials in nature, snow is thermodynamically an extremely unstable substance, as a result of its existence close to its own melting point (Perla and Martinelli, 1976). This instability is revealed by the drastic change or metamorphism of snow crystals which begins as soon as the snow is deposited. While the temperature of the snowpack determines the *rate* of metamorphism, the temperature gradient across the snowpack layers largely determines the *type* of metamorphism (Perla and Martinelli, 1976). Generally three types of metamorphism can take place in a seasonal snowcover (Sommerfeld and LaChapelle, 1970); temperature gradient metamorphism, equi-temperature metamorphism and melt-freeze metamorphism. Each has a profoundly different effect on subsequent snowpack stability.

Researchers have long realized the significance of temperature gradient ('constructive') metamorphism in the development of extreme snowpack instability (e.g. Seligman, 1936; LaChapelle, 1966; 1970; Armstrong and LaChapelle, 1976). The process of temperature gradient metamorphism as a result of negative gradients in the snowpack (lower temperatures toward the snow-air interface) are described by Perla and Martinelli (1976). LaChapelle (1969) provides an excellent description of 'depth hoar', the end product of temperature gradient metamorphism. Its formation generally in the basal layers of the snowcover results in a weak foundation for successive layers. In extreme cases snow depletion for vapour supply may produce cavities near the snow-ground interface (Giddings and LaChapelle, 1962). The significance of depth hoar in avalanche hazard formation is summarized by Fraser (1978, p.112):

> "Even if constructive metamorphism does not actually precipitate an avalanche it may well reduce the Stability Index to the point where the slightest increase in sheer(sic) stress could destroy the equilibrium".

In winter climates characterized by low snowfall and cold temperatures - conditions ideal for negative snowpack temperature gradients and temperature gradient metamorphism - the majority of the lubricating layers[1] of avalanches may consist of depth hoar grains (e.g. LaChapelle and Armstrong, 1976).

Several cold-room experiments have been carried out in an attempt to elucidate on the exact conditions necessary to produce temperature gradient metamorphism (Akitaya, 1967; Marbouty, 1980). The growth of depth hoar in field conditions has been observed by Armstrong (1980). Temperature gradient thresholds for this type of metamorphism have been determined by Giddings and LaChapelle (1962), Akitaya (1967) and more recently by Marbouti (1980). A lower vapour pressure gradient threshold is perhaps more significant than a temperature gradient threshold (Armstrong, 1980), because the growth and subsequent shape of depth hoar crystals have been shown to be dependent also on specific temperature (Giddings and LaChapelle, 1962; Marbouty, 1980). However, this remains difficult to measure in the field. Giddings and LaChapelle (1962) and Marbouty (1980) have also investigated the effect of snow density, original crystal type and ambient atmospheric pressure on depth hoar development; Marbouty has determined lower and upper snow density thresholds outside of which temperature gradient metamorphism should not occur.

The persistence of depth hoar for long periods of time, even after removal of the temperature gradient responsible for its formation, produces long-term latent instability in the snowpack. Research has indicated that depth hoar is very resistant to subsequent densification, and continues to exhibit low mechanical strength through the entire winter (LaChapelle and Armstrong, 1976). The zone of minimum strength in the snowpack has also been found to correlate closely with the zone of maximum temperature gradient during depth hoar formation (Bradley *et al*, 1977; Adams and Brown, 1982).

In the absence of a sufficiently steep negative temperature gradient to produce temperature gradient metamorphism, vapour transfer in the snowpack is limited to individual snow grains (Ramseier and Sander, 1966). Termed equi-temperature ('destructive') metamorphism, this process produces two important changes in new snow: a general rounding of snow grains in the process of obtaining a more stable relationship

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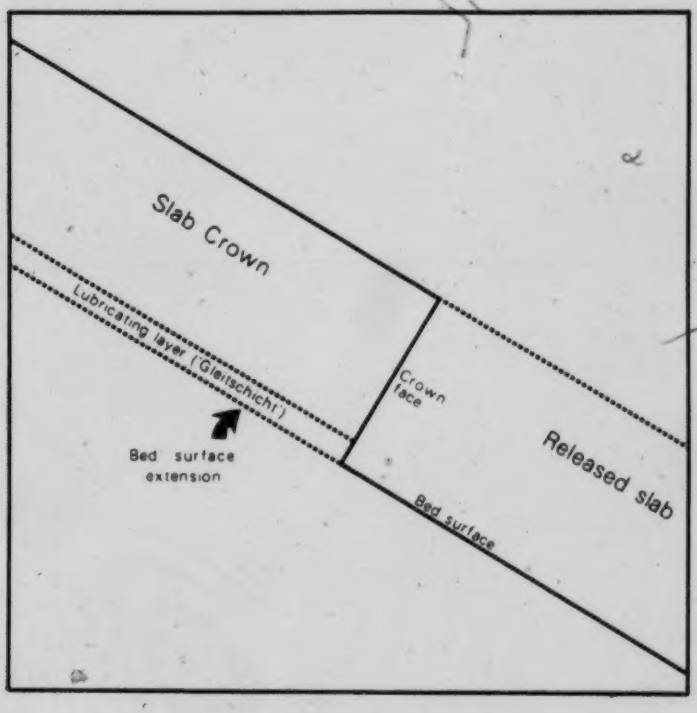
[1]A layer of cohesionless grains between an avalanched snow slab and the slab substratum, on which the released slab slides (Figure 1.1).



Source: *Stethem and Perla (1980)*

Figure 1.1 Idealization of the slab crown region

between surface area and volume, and a strenghtening of the ice skeleton by the formation of intergranular bonds (necks) through a process called sintering (Ramseier and Sander, 1966). The end result is "... fine-grained snow that can be compacted by external forces to a high density and strength" (de Quervain, 1963).

Because of its stabilizing effect on the snowcover, equi-temperature metamorphism has received relatively little attention from avalanche researchers. Most work has concentrated on the rate of metamorphism, the mechanics of sintering, and resulting snow strengths (e.g. Yosida, 1963; Ramseier and Sander, 1966; Keeler, 1969; LaChapelle, 1969; Perla and Martinelli, 1976; Fraser, 1978).

The rate of equi-temperature metamorphism has been found to correlate closely with absolute temperature (Ramseier and Sander, 1966; Perla and Martinelli, 1976). However, at a constant temperature Keeler (1969) maintains that snow strength is a direct function of the number and size of intergranular bonds. The ability of equi-temperature metamorphism to affect almost all types of grains, including depth hoar, has been widely recognized. However, as noted earlier altered depth hoar will continue to exhibit significantly lower mechanical strengths than other types of grains (LaChapelle, 1969).

Melt-freeze metamorphism contributes to snowpack instability primarily in the spring, as it requires the cycling of above- and below-freezing temperatures (Keeler and Weeks, 1968; Sommerfeld and LaChapelle, 1970; Perla and Martinelli, 1976). Free water produced by melting at the snow surface travels downward through the snowpack until it freezes on contact with a cold layer or is blocked by a hard layer. Polygranular units formed in the saturated section are alternately tightly bonded by frozen meltwater when temperatures drop below 0°C, and only by surface tension when the temperatures rise above freezing. Thus such melt-freeze 'corn' snow can vary from extremely weak to enormously strong.

Many researchers (Ambach and Howorka, 1966; Moskalew, 1966; Keeler and Weeks, 1968; Armstrong, 1976; Perla and Martinelli, 1976) have emphasized the unstable nature of corn snow in the thaw phase, especially when associated with underlying impermeable surfaces such as ice layers or the ground. The propensity of these surfaces to act as sliding planes when lubricated by meltwater has been well documented (Gand, in der and Zupancic, 1966; Armstrong, 1976; Perla and Martinelli, 1976).

Since melt-freeze metamorphism requires the introduction of meltwater into the snowpack, the role of spring-time surface crusts in the prevention of surface melting, meltwater percolation and subsequent instability has been examined (Gardner and Judson, 1970). Results indicate a correlation between crust thickness and delay of instability and avalanching.

Knowledge of the mechanical properties of seasonal snow is based primarily on mathematical models and cold-room experiments. The mechanical properties of a natural snowcover have been difficult to study, not only because of the unsystematic change of these properties from layer to layer, but also because they are time dependent (Hobbs, 1965).

The effect of snow density on its strength has been examined by Mellor (1968). He feels that an increase in density usually produces an increase in strength as well as an increased resistance to deformation. In low density snow, structure largely determines the strength of the snow (Mellor and Smith, 1966). The relation between snow temperature and strength is largely unknown, but some evidence indicates that snow undergoes rapid increases in strength with small decreases in temperature (Mellor and Smith, 1966; Roch, 1966). The great reduction in snow strength in isothermal[1] conditions is well known, however (Ambach and Howorka, 1966; Gardner and Judson, 1970; Armstrong, 1976), and is closely associated with melt-freeze metamorphism. The strength of snow is ultimately a product of cohesion between crystals coupled with resistance to breakage of the crystals themselves. Three means of cohesion are employed by snow crystals and grains (Fraser, 1978): bonding (in settled equi-temperature snow), interlocking of dendrites and crystal projections (in new snow) and capillary action (in wet snow).

On an inclined surface, deformation of the snowpack produces compressive and shear stresses. In addition, Perla and Martinelli (1976) identify several sources of tensile stress; its role in snowpack failure is examined in detail by Narita (1980) and Watanabe (1980). The shear stress component produces creep[2] and glide[3] in the snowpack (Brown *et al*, 1973; McClung, 1980; 1981b). The relation between snowpack stresses and

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[1]The entire snowcover at a temperature of 0°C.
[2]Internal deformation of the snow skeleton.
[3]Slippage of the snowpack along the ground.

avalanche formation is summarized by Price (1981, p.159):

> "The point of critical instability for avalanche release is reached when the component of force parallel to the slope exceeds the shear strength of the bond between the surface snow and the underlayer."

The fracture mechanics of snow are poorly understood, although the basic principles of snowpack failure are known (see Perla and Martinelli, 1976). Brittle fracture of snow in actual avalanche release has been examined by several authors (Ballard and McGaw, 1966; Keeler and Weeks, 1968; Sommerfeld, 1969; Bradley, 1970; Perla and LaChapelle, 1970; Brown *et al*, 1972; Lang and Brown, 1973; Johnson, 1980; McClung, 1981a). Accoustic emissions by unstable snow prior to failure have also been investigated for their possible use in evaluating developing avalanche conditions (McNair and Wolfe, 1977; St. Lawrence, 1980).

For an in-depth treatment of snow mechanics the reader is referred to Mellor (1968; 1974).

1.2.2 Weather and avalanches

Weather plays a critical role in avalanche formation in climates where releases occur primarily as the result of instability within newly deposited snow ('direct action' avalanches) (LaChapelle, 1966; Mellor, 1968). In climates where instability is generally the product of structural weaknesses in older snow layers, weather events often provide a trigger for snowpack failure. However, LaChapelle (1974; 1980) notes a marked lack of agreement between avalanche workers regarding the most significant precipitation, wind and temperature parameters affecting snow stability and avalanche triggering. The combination of significant parameters is ultimately a function of the climatic and physiographic characteristics of the area in question.

Eight weather-related parameters have generally been recognized to be important in instability and avalanche formation. LaChapelle (1967, p. 1169) notes that "each has survived on the pragmatic basis of demonstrated usefulness". These parameters are new snow depth, snowfall intensity, precipitation intensity, crystal type, new snow density, rate of settlement and wind speed and direction (LaChapelle, 1966). In addition, air temperature has been identified as a further contributing factor (LaChapelle, 1974;

Armstrong and LaChapelle, 1976). Most avalanche researchers and forecasters (e.g. Schaerer, 1962; Martinelli, 1971; Israelson, 1978; Simms, 1978; Williams, 1978) utilize some combination of these. Secondary factors such as atmospheric humidity and solar radiation may also play a role (Williams, 1981), but have limited practical applicability.

Snowfall has been identified as the single most important cause of snowpack instability and avalanche triggering (Zingg, 1966; Judson, 1967; de Quervain, 1975; Perla and Martinelli, 1976; Price, 1981; Roch, 1981). Most research on its role in avalanche formation has attempted to establish lower threshold values of total new snow amounts (U.S. Forest Service, 1953; Schaerer, 1962; Judson, 1967; Perla, 1970; de Quervain, 1975). While most are in general agreement (approximately 25-40 cm), exact values appear to be dependent on local terrain, snowpack and storm characteristics.

The alpine snowpack is also sensitive to the rate of stress application (Perla, 1970). Thus snowfall intensity, and particularly precipitation intensity (P.I.), defined as the product of snowfall intensity and snow density, are equally as important as new snow depths. Several researchers (Atwater, 1952; 1966; LaChapelle, 1966; Perla, 1970) have attempted to establish P.I. thresholds in the formation of avalanche hazard; LaChapelle (1966) notes that a threshold must be exceeded in order to overcome the stabilizing influence of metamorphism and settlement. The measure of mass per unit area has also been utilized to express critical rates of new snow loading (Judson, 1967). Perla (1977) has calculated the rate of stress application on a snowpack necessary for intense avalanche activity.

The relation between the nature of new snow crystals and avalanche formation has not been explained to any great degree. However, higher density rimed new snow[1] and graupel[2] have been documented to be associated with avalanches, particularly when they are deposited under warm temperatures and high winds (Atwater, 1952; 1966; Judson, 1967; LaChapelle, 1967; 1969). Higher density new snow in general is more likely to produce instability and avalanches because of the more rapid accumulation of weight and the fact that it is more prone to slab formation. 'Needle' and 'sheath'-shaped new snow crystals have also been linked to avalanche activity, when these are again deposited under

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[1]New snow coated with frozen supercooled water droplets. This condition is common in climates which produce abundant supercooled clouds and is less common in cold, dry continental climates (LaChapelle, 1969).
[2]Snow crystals so heavily rimed that they form pellet-like rounded grains.

warm and windy conditions (LaChapelle, 1969).

The importance of rain must not be underestimated in the development of avalanche hazard in maritime climates. A significant number of major avalanches are triggered by rain immediately following a heavy snowfall (Schaerer, 1962; LaChapelle, 1966; Hutcheon and Lie, 1978), as a result of its destabilizing effect on new snow. Few data are available on actual amounts of rain necessary to produce avalanching, apart from some derived from specific regional studies (e.g. Ambach and Howorka, 1966; Gardner and Judson, 1970). In continental climates winter rains occur so infrequently that they are an insignificant factor in avalanche formation (Zingg, 1966).

Loading of avalanche slopes by wind and subsequent slab formation is one of the most significant causes of avalanches (Kotlyakov and Plam, 1966; Roch, 1981). In continental climates wind may in fact contribute more to avalanche formation than snowfall (Judson, 1964). This conclusion seems warranted in light of the fact that avalanches in the Rocky Mountains of the United States have been observed to be markedly confined to lee slopes (LaChapelle, 1966).

The phenomenon of wind transported snow has received much attention (Mellor, 1965; Kotlyakov and Plam, 1966; Oura, 1967; Oura *et al*, 1967; Bergen, 1970; Föhn, 1980; Iversen, 1980; Maeno *et al*, 1980; Schmidt, 1980; Tabler, 1980a; 1980b; Takeuchi, 1980; Barry, 1981). However, most research has been of a highly theoretical nature and concerned with the mechanics of blowing snow and associated mass flux, with limited applicability in the field. Tesche and Yocke (1978) review some attempts to apply numerical wind models to avalanche hazard evaluation.

Attempts to minimize the effects of blowing snow have primarily been through the design of snow fences and jet roof structures to disrupt air flow over ridge lines (Mellor, 1968; Campell, 1975; Perla and Martinelli, 1976; Norem, 1978; Tabler, 1980a). These have been largely successful, in part due to the very localized nature of blowing snow processes (Kotlyakov and Plam, 1966; Föhn, 1980).

Many researchers have endeavoured to establish threshold wind speeds for snow transport and subsequent avalanche formation (Schaerer, 1962; Atwater, 1966; Judson, 1967; LaChapelle, 1967; de Quervain, 1975). The minimum effective wind speed for creating such conditions is thought to be approximately 6.7 m s^{-1} (Price, 1981, p.162),

although some research indicates that speeds of only 3.3 m s^{-1} can affect avalanche formation (Schaerer, 1962). Exact values are a function of the cohesiveness of the snow surface (Pugh and Price, 1954, in Barry, 1981, p.218; Tabler, 1975) and the terrain configuration.

Because snow slabs often contain large masses of snow and great amounts of potential energy (Perla and Martinelli, 1976), their formation is an important facet of avalanche formation.

Slab formation is generally thought to be the result of pulverization of snow during transport (Barry, 1981, p.218), which because of the resulting small particle sizes and high snow densities allows easy packing (LaChapelle, 1969). Varying hardnesses of slab are usually attributed to the velocity and duration of wind as well as to the intensity of snowfall (Seligman, 1936; Judson, 1967; LaChapelle, 1967).

The role of air temperature in the development of snowpack instability and in avalanche triggering is confined primarily to the spring months, when above-freezing temperatures push the snowpack toward isothermal conditions. Studies in the Ötztal Alps of Austria have shown a nearly synchronous relationship to exist between mean daily air temperature, free water content of the snowpack and wet snow avalanching (Ambach and Howorka, 1966). In the Davos-Parsenn area of the Swiss Alps rising air temperatures are the primary cause of the majority of springtime avalanches (Zingg, 1966). More recent research in the San Juan Mountains of Colorado has indicated that air temperature provides the most readily available index of avalanche potential in the spring (Armstrong, 1976).

Above-freezing air temperatures can also affect the stability of a midwinter snowpack, a situation relatively common in maritime climates where freezing levels fluctuate widely. Particularly high levels of avalanche hazard can develop when warm weather is preceded by snowfall (Schaerer, 1967).

The effect of subfreezing air temperatures on avalanche formation is not clearly understood. Judson (1964; 1967) however has observed that slab avalanches in continental climates tend to release when temperatures are low or falling. Other authors (e.g. Perla and Martinelli, 1976) have also suggested a 'temperature release' mechanism whereby abrupt changes in air temperature trigger avalanche release. However, this

mechanism is questionable since snow is a poor thermal conductor (Perla and Martinelli, 1976).

1.2.3 Terrain and avalanches

The basic characteristics of avalanche paths have been described by several authors (e.g. Mellor, 1968; Martinelli, 1974; Perla and Martinelli, 1976). In addition, slope angle and its relation to avalanching has been extensively investigated (e.g. Mellor, 1968; Martinelli, 1974; de Quervain, 1975; LaChapelle and Armstrong, 1976; Perla and Martinelli, 1976; Stethem and Perla, 1980); as a result it has been possible to define relatively narrow ranges of slope angles for different types of avalanches. The peak of occurrence for slab avalanches is in the 35-40° range, but can occur on slopes as gentle as 25° and as steep as 55°. Loose snow avalanches require somewhat steeper slopes, in the order of 40-60° (de Quervain, 1975); exact slope angles for such releases are dependent on the angle of repose of different types of snow. Very wet, loose snow avalanches have been known to occur on slopes of only 12° (Cottman, 1966). Ultimately, the ratio of snowpack strength to downslope stress determines the exact slope angle required to produce failure.

The detailed nature of terrain, and its effect on avalanche formation has however received little attention from researchers. Although terrain asperities and slope configuration undoubtedly play a part in anchoring as well as producing stresses in the snowpack, the inhomogeneous structure of a seasonal snowcover has allowed only generalizations to be made of these relationships (e.g. Martinelli, 1974). In addition, the examination of terrain in regional studies of avalanche hazard (e.g. Armstrong and Ives, 1976) tends to have limited general application. However, the effect of the ground-snow interface condition on snow deformation has received some detailed theoretical attention (McClung, 1975; 1980).

Vegetation can be viewed as a terrain variable in avalanche studies, because it plays an important role as an anchoring mechanism for inclined snowpacks: a snow depth sufficient to cover significant vegetation is a prime requirement for avalanche formation. Thus grass covered slopes provide little support for inclined snowpacks, and serve to enhance basal glide and subsequent stress development. Dense forests, on the other

hand, are widely recognized to have an inhibitive effect on avalanche formation as a result of snowfall interception by the tree crowns and the supporting effect of the stems (de Quervain, 1979). Unfortunately, in some mountain regions such as the Rocky Mountains many avalanches start above timberline and run through the forest (Martinelli, 1974). Forest removal by fire or logging also has a destabilizing influence on mountainside snowpacks, and can result in the formation of new avalanche paths (Eidg. Institut für Schnee- und Lawinenforschung, 1979).

1.2.4 Avalanche hazard evaluation and forecasting

The evaluation and forecasting of avalanche hazard remains essentially a 'technical art' rather than an exact science, as a result of the complex nature of instability formation and avalanche triggering. LaChapelle (1966; 1970; 1980) outlines in detail the "numerical-intuitive" (Anderson *et al*, 1978) processes involved. He (1980, p.78) notes that "conventional forecasting methods embrace a sufficiently redundant data base that several inductive-logic paths exist" and that "there is more than one way to forecast an avalanche".

Efforts to develop a statistical approach to hazard evaluation and forecasting have been numerous (e.g. Obled, 1970; Bois and Obled, 1972; Judson and Erickson, 1973; Bovis, 1974; 1976; 1977; Bois *et al*, 1975), based primarily on weather data. However, it is generally conceded that such an approach will never provide an adequate tool by itself; most hazard evaluation and forecasting will continue to be based on the intuitive analysis of available weather ("analytical" [Schaerer, 1962]) and snowpack ("testing" [Schaerer, 1962]) data.

The evaluation of snowpack stability suffers from a shortage of useful tests that can be easily carried out in the field. The difficulties of setting up consistent experiments in fresh snow are largely due to the problem of structure and property variation in the vertical direction (Perla, 1969). Thus much of the theoretical research remains of limited practical use for the field worker, despite efforts by some authors to bridge the gap (e.g. Bradley and Bowles, 1967; McClung, 1977; Ferguson, 1981; Stethem and Tweedy, 1981). As a result avalanche workers requiring immediate high-reliability information on snow stability still rely on low entropy mechanical tests such as test skiing and the use of

explosives.

1.2.5 Photography in avalanche research

The use of photography in avalanche research is not new; Kahn (1966a, p.2) notes that "many sequence photographs and movies of avalanches have been made in the past", possibly because of their awe-inspiring nature. However, Kahn (p.2) also points out that "most of these photographic reproductions can give qualitative information only". As a result, a significant amount of research has devoted itself to devising photogrammetric techniques for studying the dynamics of moving avalanches.

Kahn (1966a; 1966b; 1972) has utilized terrestrial photogrammetry in the Canadian Rocky Mountains and in the Wasatch Mountains of Utah to record avalanche fracture line propagation and avalanche movement, and from this information has been able to determine the geometrical shape of the observed avalanches. Van Wijk (1967) employed a similar technique in the Canadian Rocky Mountains for mapping slopes before and after avalanches, and for providing information on the volumes of transported snow, avalanche velocities and the volumes of snow clouds.

Japanese researchers have used other photographic techniques for measuring avalanches. Shoda (1967) photographed avalanche traces from helicopters, and used this information to produce contour maps of the disturbed snow surfaces. Akitaya (1973) has attempted to use video tape recorders in the study of moving avalanches.

Most recently, motion picture photography has been employed for recording the decceleration of scale model avalanche flows in the Bridger Range of Montana (Dent and Lang, 1982).

In spite of the proven applicability of photographic techniques to the study of avalanche dynamics, the medium of photography has not been used to address the problem of documenting avalanche occurrence over an entire winter. Earlier it was noted that the difficulty of obtaining continuous detailed data on avalanche activity greatly hampers the study of the causes of avalanches. Post-event inspections of avalanche paths and debris have two serious shortcomings:

- determining the frequency of avalanches and classifying them with regard to type, size, mode of failure and distance of travel is extremely difficult,

- regardless of how reliable the available weather record is, the researcher has no accurate means of correlating short-term weather events to avalanche activity.

The practicality of time-lapse photography for monitoring natural phenomena in a severe environment was demonstrated by Banner and van Everdingen (1979). By adapting surplus military cameras to obtain time-lapse exposures, they were able to successfully record the growth and degradation of frost blisters in the Northwest Territories, Canada. Nevertheless, time-lapse photography as a means of continuously monitoring avalanche slopes has not been investigated.

1.2.6 Avalanche research in Kananaskis Country

Avalanche research has not been extensive in Kananaskis Country, although studies to date have dealt with avalanches there both as a geomorphic phenomenon and as a source of hazard for people.

Tarquin (1977) has investigated sediment transport in snow avalanches and resulting geomorphic features. More recently, Gardner (1983) has commented on the erosional characteristics of late-spring wet snow avalanches in the Highwood Pass area. Gardner *et al* (1983) present a lengthy discussion of avalanches as a geomorphic agent capable of modifying the mountain landscape, with particular emphasis again on the Highwood Pass area.

Gunderson (1978) provides a preliminary analysis of avalanche hazard along the Smith-Dorrien Road and Highway 40 through Highwood Pass. It consists primarily of the identification of avalanche paths affecting these routes. Steel (1982) offers further insights into the nature of the hazard at selected paths along Highway 40; analyses of slope morphology and vegetation were carried out to furnish information on avalanche magnitudes and return intervals. Recently, Gardner *et al* (1983) have produced a map of avalanche potential in the Highwood Pass area, based on direct observations in the spring as well as on indirect evidence of avalanche activity. Stethem and Associates Ltd. (1983) have compiled a detailed atlas of avalanche paths threatening the Smith-Dorrien Road. The most comprehensive mapping of avalanche hazard sites in Kananaskis Country was completed by McPherson *et al* (1983). Their report includes a general avalanche hazard map for a large part of the region. In addition, several potential high-risk areas, both in the

backcountry and adjacent to transportation routes, were selected for detailed study. Dendrochronological techniques were employed for establishing the frequency of high magnitude avalanches on paths in these areas.

To date, research on the avalanche hazard in Kananaskis Country has accomplished two things:

- it has identified in a general way large backcountry areas that are hazardous, and in a more precise way identified specific avalanche paths that threaten both backcountry and transportation routes, and
- it has supplied some preliminary data on the return intervals of large avalanches on these paths.

However, with respect to the increasing numbers of backcountry recreationists in Kananaskis Country, the above accomplishments have serious shortcomings:

- the mapping of backcountry avalanche hazard over large areas has limited application, because most unwary skiers are trapped by avalanches on small paths that are virtually unmappable on the map scales available (Perla and Martinelli, 1976; Ives and Plam, 1980).
- the dendrochronological techniques used to establish the frequency and magnitude of avalanches are only able to identify past events that were destructive enough to damage the sampled trees. They can offer no indication of the frequency of smaller avalanches which nevertheless are dangerous to backcountry travellers.

Except for very brief generalizations (e.g. Stethem and Associates Ltd., 1983; Gardner *et al*, 1983), the types and causes of avalanches in Kananaskis Country have not received any attention from researchers. Based on work carried out for this thesis however, McPherson *et al* (1983) have included a discussion on the causes of snowpack instability, the triggering mechanisms of avalanches and the types of avalanches on two paths in the region.

1.3 Study Area Locations

Two large avalanche paths were used as study areas during the winter of 1982-83. Although both are located in Kananaskis Country, Alberta, they are approximately 30 km distant from each other and thus represent avalanche conditions in two different parts of the region. The "Mount Inflexible #3" path is located near the Fortress Mountain ski area, along the northeastern flank of the Kananaskis Range (Figure 1.2), while the Highwood Pass avalanche slope is located directly at Highwood Pass, further south and in Kananaskis Provincial Park (Figure 1.2). Sections 1.4 to 1.6 discuss the regional characteristics of Kananaskis Country: the avalanche paths, or study areas, are described in detail in Section 1.7.

Kananaskis Country is located in southwestern Alberta, in the Front Ranges of the Canadian Rocky Mountains. The region lies at approximately 115° west longitude and 51° north latitude (Figure 1.2), 75 km west of the city of Calgary. It is bounded on the west by the province of British Columbia and by Banff National Park.

Kananaskis Provincial Park, approximately 508 km² in size (Alberta Recreation and Parks, 1978), constitutes the core of Kananaskis Country, and is centered on the Kananaskis Lakes (Figure 1.2). Both it and the majority of Kananaskis Country are easily accessible on Highway 40, running south from the Trans-Canada Highway. During the summer Highway 40 also provides access to the region from the town of Black Diamond to the southeast. The Smith-Dorrien road accesses the Kananaskis from the town of Canmore via the Spray Lakes reservoir, but is not currently open to the general public.

1.4 Physical Setting

The physiography of Kananaskis Country exhibits an extremely rugged character, with a geologically controlled NNW-SSE orientation to major valleys and mountain ranges (Smith, 1979; Gardner *et al*, 1983).

The region is characterized by a notable lack of extensive level ground, with the exception of the gently rolling topography surrounding the Kananaskis Lakes. Steep slopes with a mean angle of 30° (Smith, 1979), separating ridges from U-shaped valleys, are predominant. Slope angles also tend to increase away from the major valleys. Relief in the region is significant, with a local maximum of up to 2000 m (McPherson *et al*,

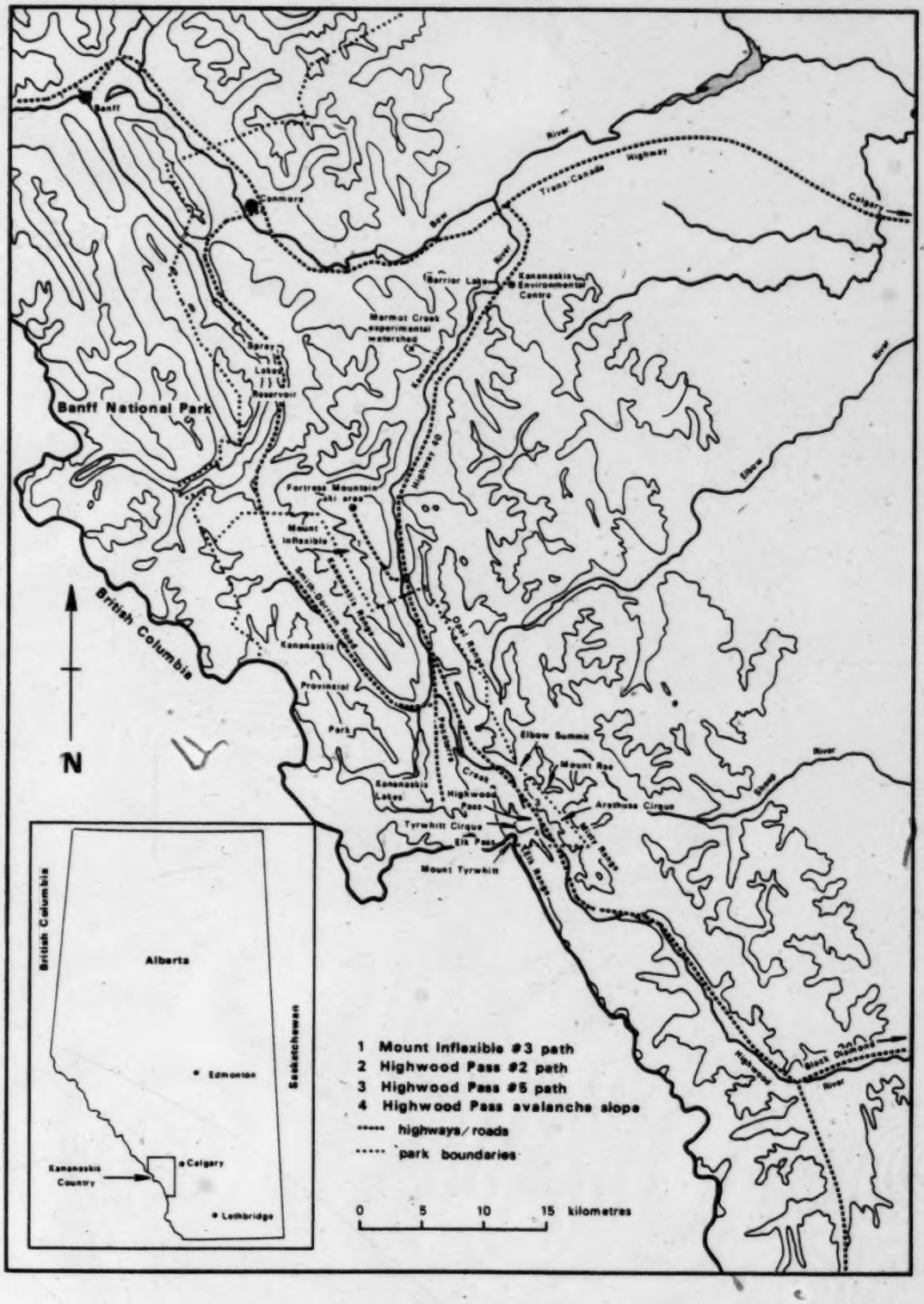


Figure 1.2 Study area

1983). Elevations increase as one moves from the Bow River valley south and west toward the Continental Divide; they range from 1390 m at Barrier Lake at the northern boundary of Kananaskis Country to 3224 m at Mount Rae in the Highwood Pass area in Kananaskis Provincial Park.

The geological structure of Kananaskis Country has primarily been shaped by orogenic deformation of sedimentary strata. Extensive folding and thrust faulting during the Laramide orogenies (Gardner *et al*., 1983) resulted in older Paleozoic formations being thrust eastward over younger Mesozoic rocks (Wheeler *et al*., 1972). These massive thrust sheets are characterized by a moderate dip to the west and steeper east-facing scarps. Downfaulting of several rock units following this resulted in an extremely rugged landscape (Smith, 1979).

Pleistocene glaciations have significantly altered the structural morphology fashioned by older mountain building periods. The action of glacial ice resulted in the steepening of scarp slopes, removal of valley-side spurs and the formation of small cirque valleys (McPherson *et al*., 1983). Large valleys in the region are generally flat-bottomed as a result of glacial action originating at the Divide. The Kananaskis River valley is a prime example of this type of catenary trough (Plate 1.1).

The present character of the topography in Kananaskis Country exerts a significant influence on the nature of avalanching. The large number of northeast-facing slopes (Gardner *et al*., 1983), coupled with prevailing northwesterly to southwesterly winds (Storr, 1973 and this author), results in the presence of numerous lee-facing slopes. The steepness of these scarps enhances avalanche activity on them; it is especially evident along the northeastern flank of the Kananaskis Range, where numerous avalanche paths descend to the valley floor (Figure 1.2 and Plate 1.1). The removal of valley-side spurs by glacial ice has also produced long, relatively steep , concave valley-side profiles which are ideal for avalanching (McPherson *et al*., 1983). A mean elevation of 2300 m in the region (Gardner *et al*., 1983) places extensive areas above timberline, where inclined snowpacks are robbed of the anchoring effects of forest, thus further enhancing avalanche formation.

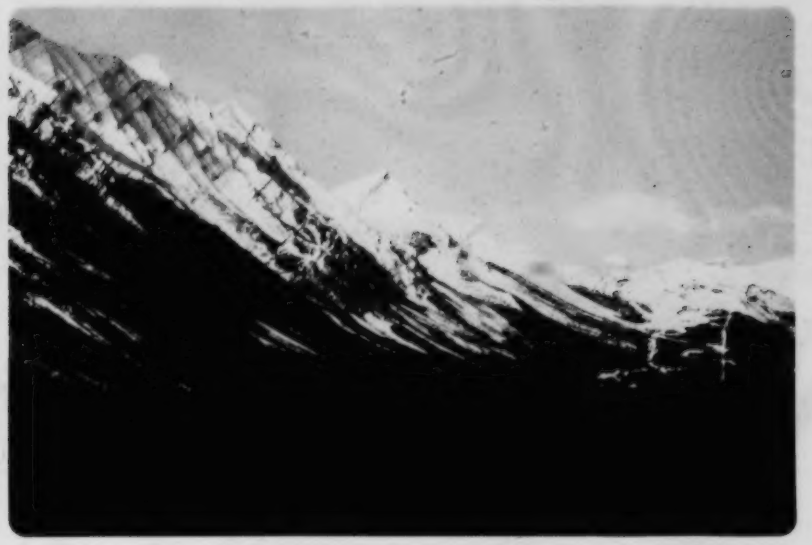


Plate 1.1 Kananaskis River valley immediately north of Kananaskis Lakes. Photo taken looking north. Kananaskis Range to left of photo.

1.5 Vegetation

Ogilvie (1969) and Hettinger (1975) identify in Kananaskis Country four altitudinally zoned vegetation divisions, which with increasing altitude are: lower montane forest, forest-tundra ecotone, alpine tundra zone, and a relatively sterile high altitude rock barren. These are reflected by a predominance of conifers, primarily Lodgepole Pine (*Pinus contorta*), in valleys and on lower slopes, replaced at higher elevations by a mixture of Engelmann Spruce (*Picea engelmannii*) and Subalpine Fir (*Abies lasiocarpa*), which in turn gives way to Alpine Larch (*Larix lyallii*) and tundra above timberline (Sneyd, 1982).

Baig (1972) notes the autoecological features of local timberlines in Kananaskis Country, including differences due to avalanching, slope and aspect. However, they are generally located between 1830 m and 2290 m (Sneyd, 1982). Sneyd also observes that 69% of all forest in Kananaskis Country consists of seral species, illustrating the importance of past disturbance, especially fire (e.g. Patterson, 1961, in Smith, 1979) in the region.

Baig (1972) and Plesnik (1973) inspected the subalpine forest near Highwood Pass and noted a closed canopy of Subalpine Fir, Engelmann Spruce, Alpine Larch and Whitebark Pine (*Pinus albicaulis*) to an upper tree line of 2100 to 2300 m. Trottier (1972), from his work in Arethusa Cirque (see Figure 1.2), has compiled the most exhaustive vegetation inventory in the alpine tundra zone. Exposed ridges and other terrain with low winter snow depths are characterized by communities of Snow Willow (*Salix nivalis*), Mountain Avens (*Dryas octopetala var hookeriana*) and *Kobresia myosuroides*. More protected sites with deep winter snowcovers were observed to host communities of mountain heaths (*Phyllodoce* spp.), Rocky Mountain White Heather (*Cassiope tetragona*) and sedges (e.g. *Carex nigricans*). Creek beds and other depressions in the cirque are host to Arctic Willow (*Salix arctica*) and Barratt's Willow (*Salix barratiana*). Trottier also noted a meadow rue association (*Thalictrum occidentale*) on steep avalanche slopes in the Highwood Pass area.

1.6 Climate

Kananaskis Country is dominated by a cold subhumid continental climate whose distinctive characteristics give rise to a winter snowpack structure that exhibits significant control over the nature of avalanching.

The winter climate is dominated by the presence of cold, dry continental polar air; the Rocky Mountains effectively bar the long-term presence of mild Pacific air from the region (Longley, 1972; Nkemdirm and Weber, 1976). The net result is low to moderate winter precipitation levels (Lee, 1969; Powell, 1977). During the period from October to April much of the precipitation is produced by the upslope flow of shallow westward trending arctic air which generates widespread stratiform cloud (Reinelt, 1970). Snowfalls are generally light and composed of low density snow. From September to April Reinelt found this orographic component to account for over 50% of the precipitation during this period. Lester (1974), on the other hand, attributes the light winter snowfalls to frontal activity as a result of moist Pacific air overriding the colder polar air, with accompanying sharp altitudinal temperature inversions (Kirby, 1973). These incursions of Pacific air also result in the short-lived chinook winds, producing extremely warm, dry and windy conditions. Chinooking is a relatively common occurrence in the Front Ranges, occurring on average twenty-nine times between the months of December and February (Longley, 1967).

Spring is characterized by the increasing dominance of modified Pacific air masses (Rheumer, 1953). Interaction of the cold, dry polar continental air mass with this moist maritime air results in frontal activity and heavy, wet snowfalls (Janz, 1976) as well as rainstorms (Warner, 1973; Thompson, 1976, in McPherson *et al*, 1983).

These macro-scale climatic patterns are often obscured by meso and micro-climatic variations (Smith, 1979). Barry (1981, p.10) describes in mountain regions a mosaic of "topoclimates" at a scale of tens to hundreds of metres as a result of slope and aspect variations. He doubts whether the "concept of a 'regional mountain climate' has much validity or value". Rather, he feels "it is more meaningful to describe the typical range of climatic elements produced in particular topographic situations, according to the type of airflows that occur, bearing in mind the major controls of altitude, latitude and continental location" (p.11).

1.6.1 Precipitation

The mean annual precipitation in Kananaskis Country exhibits a large range typical of Front Range climate stations (McPherson *et al*, 1983), from 419 mm at Evan-Thomas Creek (Figure 1.3) to 912 mm at Highwood Pass (Table 1.1). Sneyd (1982) has estimated mean annual precipitation to even exceed 1500 mm in areas close to the Divide (Figure 1.4). The significant differences are the result of variations in elevation, topographic situation and location with respect to the Continental Divide.

Winter (October-May) precipitation totals range from 216 mm at Evan-Thomas Creek to 528 mm at Highwood Pass, with the greatest amounts generally recorded at higher elevations (Storr and Golding, 1973, in McPherson *et al*, 1983. See Table 1.1). January is generally the driest month at these higher elevations, whereas lower elevation stations tend to record an October minimum of precipitation (Table 1.2). May tends to be the wettest month although higher elevation stations record equal amounts of precipitation in the month of June (Table 1.2).

The proportion of annual precipitation falling as snow is highly variable throughout Kananaskis Country. At the Kananaskis Centre for Environmental Studies (Figure 1.3) only about 30% of the total annual precipitation falls in winter. Only 40% of this winter total falls as snow (Powell, 1973). In contrast, 60% of the total annual precipitation at Highwood Pass falls as snow (Baig, 1972). During the period from October to May between 450 and 550 cm of snow may fall here, although the long-range variation is significantly higher (McPherson *et al*, 1983). In the Marmot Creek experimental watershed (Figure 1.3) as much as 70 to 75% of the total annual precipitation is recorded as snowfall at higher elevations (2135-2743 m) (Storr, 1967). A major proportion of the winter snowfall in the Kananaskis is received in April (Janz, 1976; Storr and Golding, 1976).

There is substantial evidence to suggest that precipitation increases with elevation in Kananaskis Country. In the Highwood Pass area Smith (1979), by plotting annual precipitation totals against elevation, obtained a strong positive correlation coefficient ($r=0.80$. See Figure 1.5). He suggests that precipitation in this area increases approximately 86 mm for every 1000 m of elevation gain, and even more during the winter months. Sneyd (1982) notes an increase in winter snowfall totals with elevation at the Marmot Creek experimental watershed, from 355 cm at 1754 m to 560 cm above

Table 1.1 Seasonal precipitation records

Station (see Figure 1.3)	Elevation (masl)	Oct.-May cm	May-Oct. cm	Total cm
Highwood Pass (1953-1975)	2210	52.8	38.4	91.2
Elbow Summit (1954-1971)	2180	42.9	33.9	76.8
Little Elbow Summit (1954-1981)	2180	51.6	38.6	90.2
Storm Creek Summit (1953-1977)	2073	38.7	25.6	64.3
Mud Lake (1954-1981)	1905	43.9	34.0	77.9
Kananaskis Lakes (1953-1982)	1676	27.9	24.1	52.0
Sibbald Creek Summit (1954-1981)	1555	27.2	35.8	63.0
Evan- Thomas (1954-1982)	1508	21.6	20.3	41.9

Source: McPherson et al (1983)

Table 1.2 Monthly precipitation

	Highwood Pass (1969-1981)	Kananaskis-Pocaterra (1976-1982)	
Month	Total mm	Total mm	(% snowfall)
January	49.7	25.5	(97.7)
February	62.5	38.6	(99.0)
March	67.4	43.7	(99.8)
April	84.4	34.0	(91.8)
May	97.8	78.9	(49.3)
June	99.5	57.2	(13.3)
July	59.5	51.3	(0)
August	71.6	72.4	(0)
September	62.8	39.4	(14.0)
October	52.8	21.9	(76.3)
November	66.8	32.7	(97.6)
December	81.8	71.6	(94.0)

Source: McPherson et al (1983)

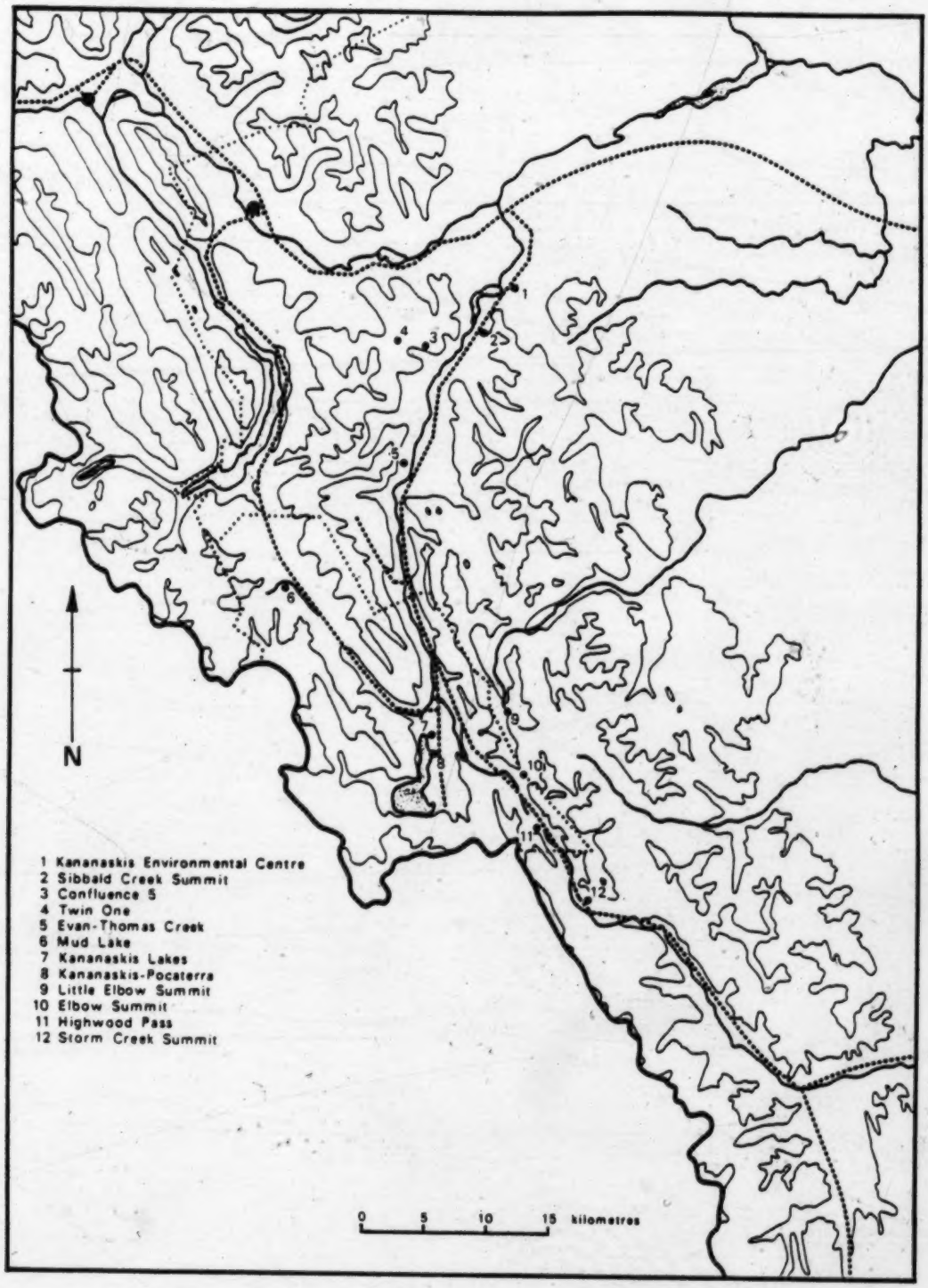
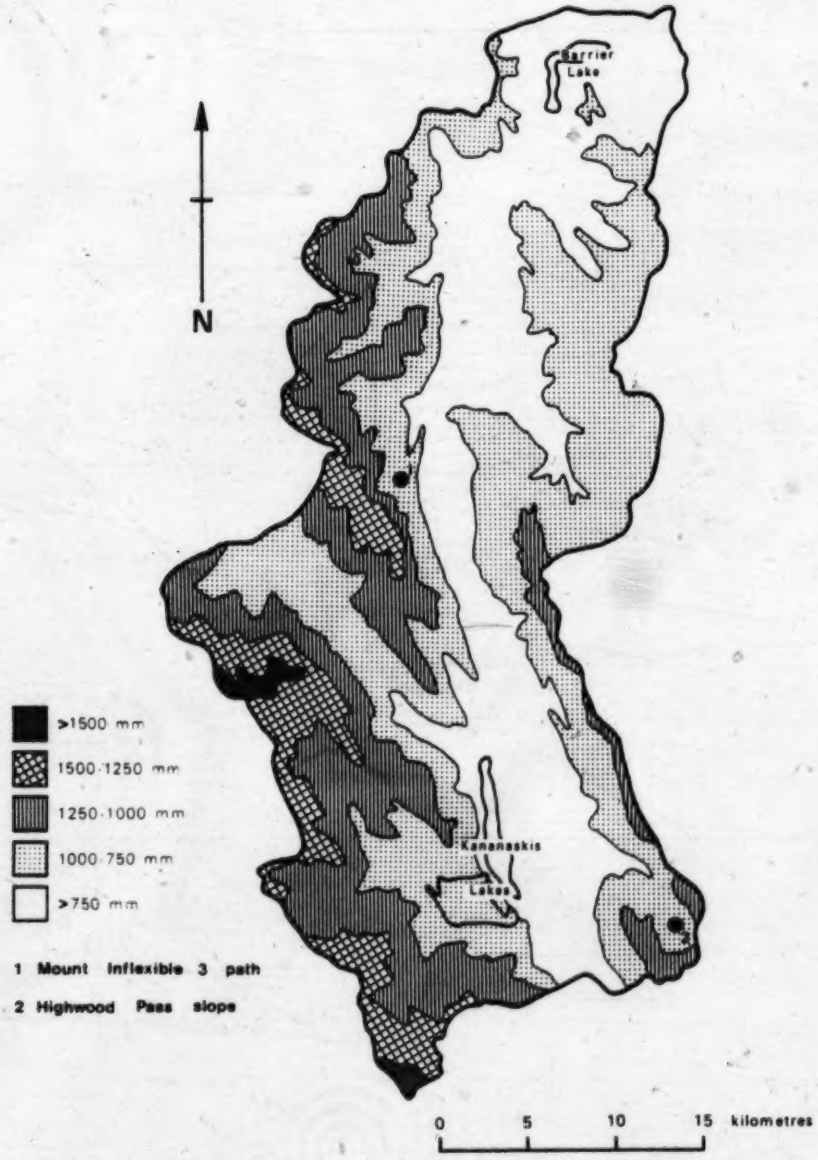
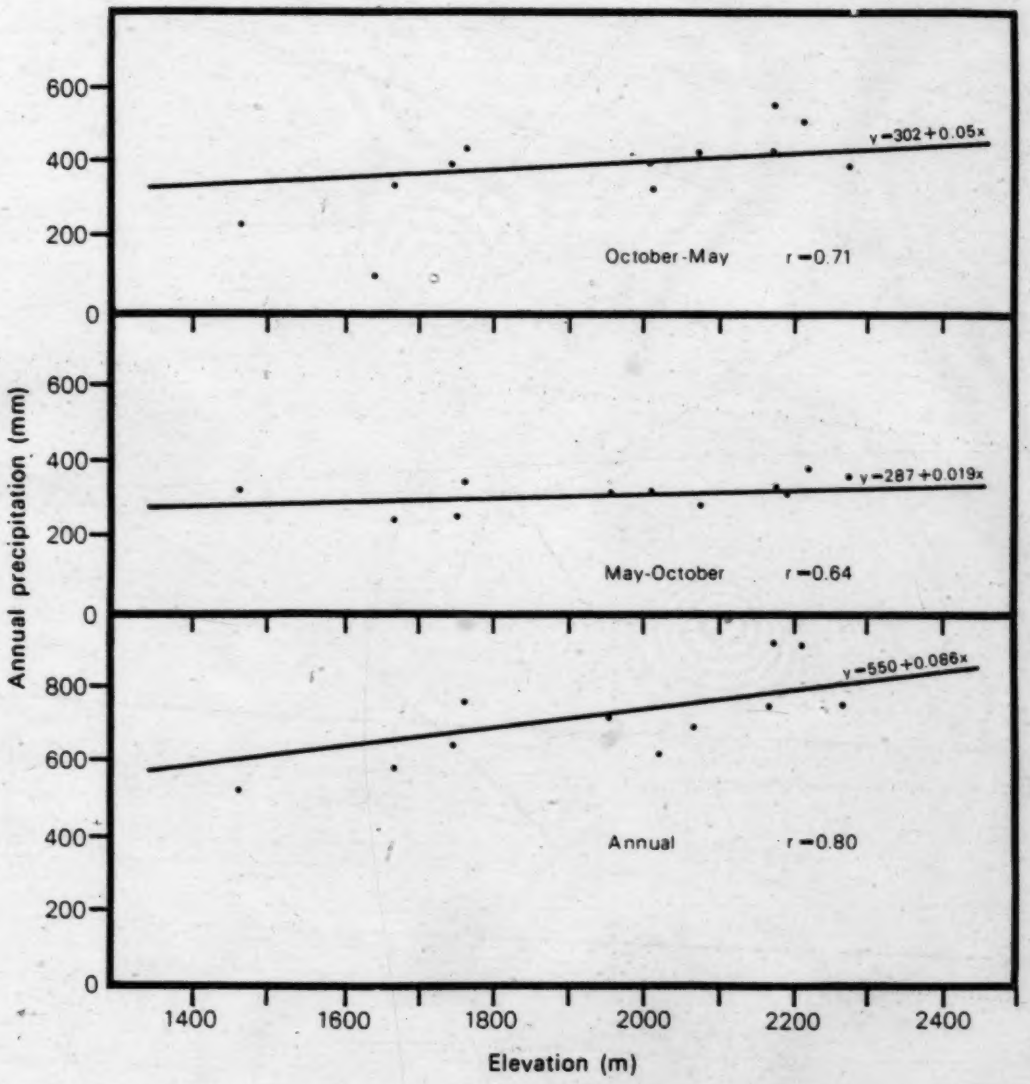


Figure 1.3 Climate stations in Kananaskis Country



Source: *Sneyd (1982)*

Figure 1.4 Estimated average annual precipitation in the Kananaskis watershed



Source: *Smith (1979)*

Figure 1.5 Precipitation - elevation relationships in the Mount Rae area

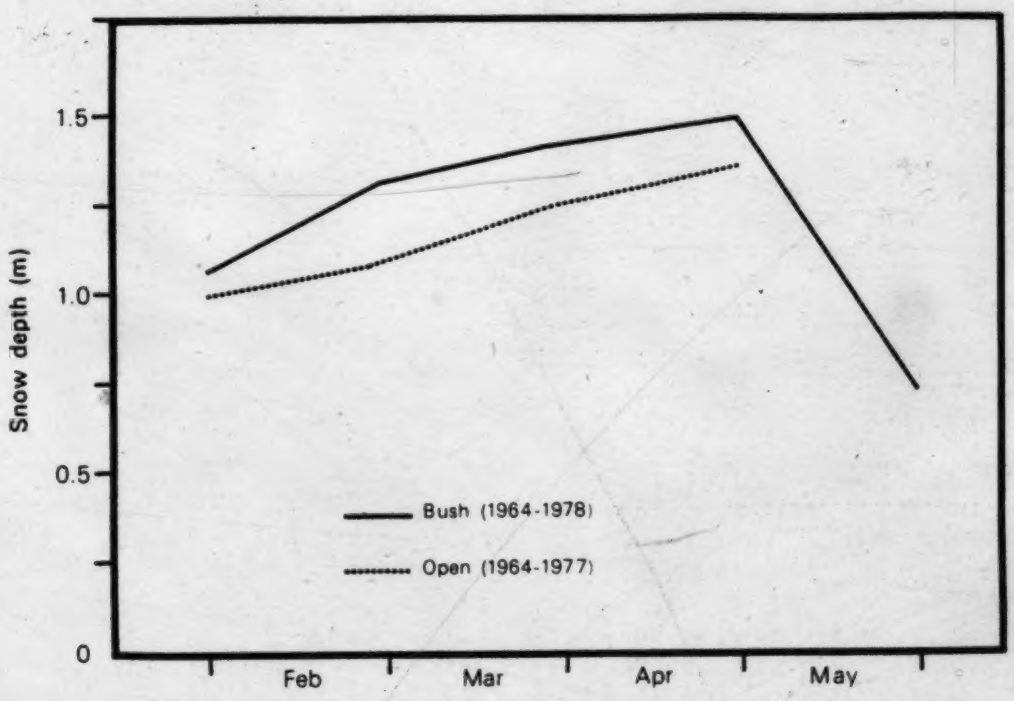
2288 m. Golding (1974) found snow water equivalents at Marmot Creek to increase with elevation at rates of 1.25 cm to 3.92 cm per 100 m rise in elevation. Sneyd (1982) notes however that although an elevation-precipitation relationship does exist, several factors render it invalid above a certain elevation in Kananaskis Country (p. 153):

- after saturation levels are reached in the air mass, further uplift results in a decline in precipitation,
- steep slopes and ridges characteristic of the area are not conducive to receiving large amounts of precipitation, while relatively level cirques and bowls are, and
- high winds redistribute most precipitation, especially snow, away from exposed upper slopes. However, this last point is just conjecture since little data are available for locations above 2500 m.

Sneyd offers several explanations for the higher snow water equivalents found in spring (March-April) at higher elevations (p. 182):

- spring snow, being denser, is less subject to drifting than winter snow,
- less wind activity is present in April,
- some of the stations owe their increases to generally northeast exposures, and
- the elevation-snow relationship is related to the seasonal energy balance regime.

Maximum snowpack depths in Kananaskis Country generally develop at the end of April (Figure 1.6). Unfortunately these do not represent total snowfall amounts as much is lost by redistribution by wind (Storr, 1973) and evaporation by chinooks (Golding, 1977; Louie, 1977). Wind redistribution of snow is an extremely important element of snowcover distribution in the region, typically removing it from westerly exposures and depositing it on east-facing slopes, often resulting in extensive areas of bare ground on windward slopes (McPherson *et al*, 1983. See Plates 1.2 and 1.3). Chinook temperature effects subject snowpacks to melt and evaporation (Golding, 1977; 1978). Their impact is greatest in midwinter when they are most frequent and best developed. Golding (1978) calculated potential evaporation rates during chinook conditions at Marmot Creek, and found them to equal 1.2 mm day^{-1} for 19 days in 1975 and 2.0 mm day^{-1} for 20 days in 1976.



Source: *Smith (1979)*

Figure 1.6 Mean monthly snow depth, Highwood Pass

Plate 1.2 Snowcover distribution on windward and lee slopes. Looking west to Mount Allan from Highway 40. Photo taken in February, 1983.

Plate I.3 Heavy wind transport of snow onto lee slopes, Kananaskis Range. Looking west from the Fortress Mountain ski area road. Photo taken in March, 1983.

It is interesting to note that the greatest May 1st snowpack depths such as in 1967, 1972 and 1974 (Figure 1.7) are always associated with significant April storms (Janz, 1968; Storr and Golding, 1976). This points out the importance of isolated heavy snowfalls in the development of the snowpack.

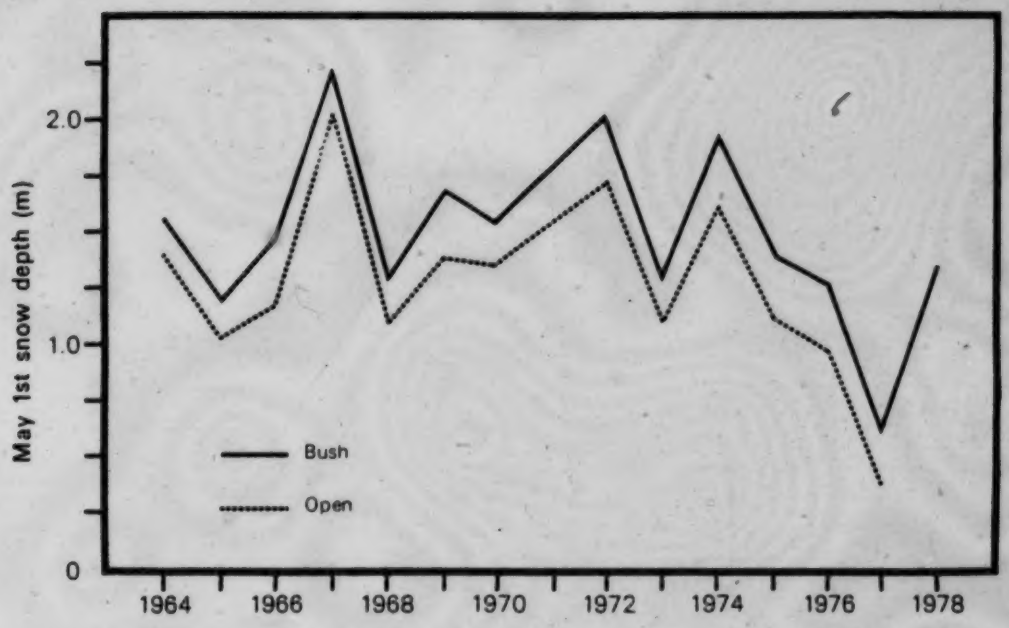
1.6.2 Wind

Although macro-scale wind patterns are relatively easy to identify in Kananaskis Country these exhibit significant adjustments to local terrain. Therefore the extrapolation of wind data from one locale to another must be done with great caution. Unfortunately, very few of these data are available in the region; stations in the Marmot Creek watershed provide most of the available information.

Wind speeds below timberline in Kananaskis Country, during the period from November to April, average 2.9 m s^{-1} (Atmospheric Environment Service, 1982). This value however is significantly higher above timberline; in the Marmot Creek watershed Storr (1973) notes a two-fold increase in wind speeds between lower levels and timberline during snowfalls. He feels a linear relationship may exist between maximum winds and elevation in the forested zone and an exponential one above timberline (Figure 1.8), but notes that more data are needed to positively establish this.

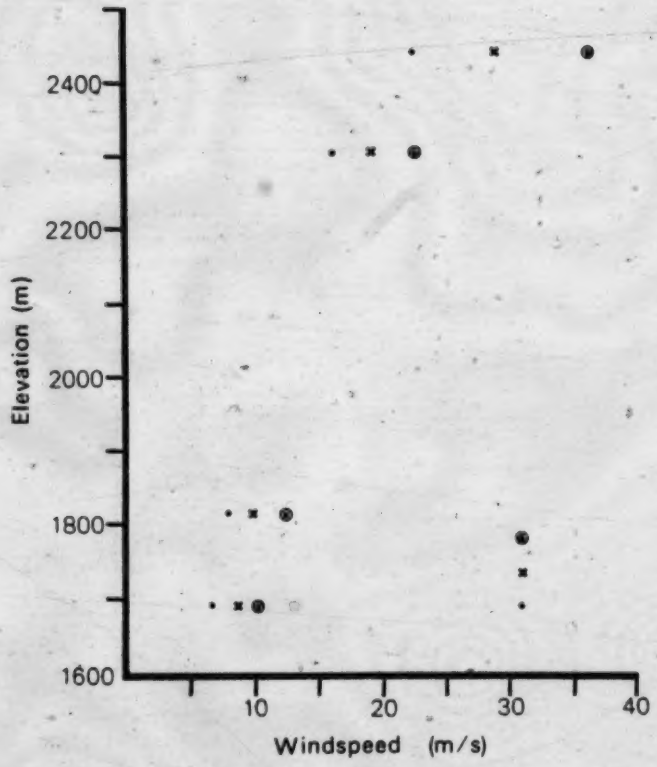
Detailed data on wind speeds and directions above timberline are scanty, with the exception of records from the Twin One station (immediately above timberline at 2285 m) at Marmot Creek (Figure 1.3). At this station wind speeds average 3.5 m s^{-1} with only rare periods of calm. Monthly mean wind speeds peak in December at 4.7 m s^{-1}. Highest values coincide with chinooking; during the period from 1974 to 1979 the highest hourly wind speed of 25.8 m s^{-1} was recorded during chinook conditions (McPherson *et al*, 1983). Trottier (1972) recorded wind speeds in a high cirque above Highwood Pass, and found the greatest monthly wind values to occur in November (4.9 m s^{-1}). Lowest mean wind speeds were recorded in May (3.0 m s^{-1}).

Considering the effect of terrain on macro-scale wind flow patterns, the extrapolation of wind direction data from Marmot Creek to other parts of Kananaskis Country is probably pointless. However, the dominance of winds originating in the southwest to northwest sector bears notice; at the Twin One station over 65% of mean



Source: *Smith (1979)*

Figure 1.7 May 1st snowpack depths, Highwood Pass



Source: *Storr (1973)*

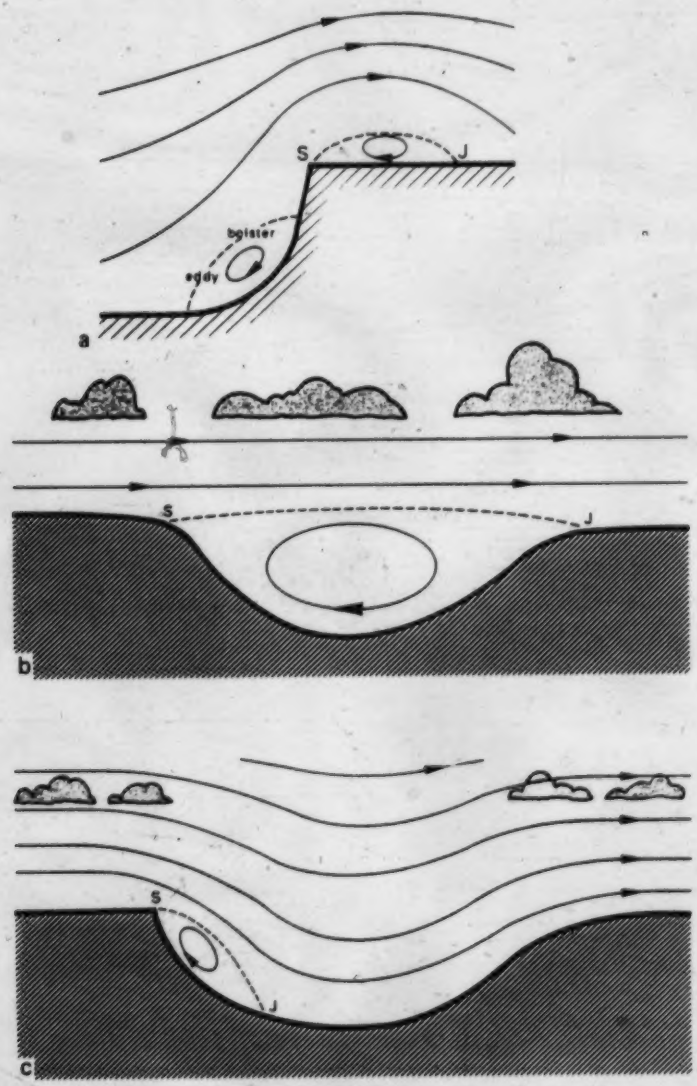
Figure 1.8 **Relationship between elevation and maximum hourly winds in the snowfall season, Marmot Creek**

daily winds were recorded from these directions (Storr, 1973). In light of the importance of Pacific air masses as a source of precipitation in the Rocky Mountains (Laycock, 1957a; 1957b; 1961), and the frequency of winter chinooks in the Front Ranges (Longley, 1967), winds originating in the west are presumably relatively common in Kananaskis Country, although they may be reoriented by terrain.

The effect of slope breaks on wind flow has not been investigated in Kananaskis Country. However, the general relationship bears examination in light of the importance of wind as a snow transport mechanism in the region.

In general, the rugged character of Kananaskis Country produces innumerable sharp breaks in slope. These act to set up more turbulence in air passing over them than gentle slopes. The tendency for airflow to separate from the ground and form vertical eddies or "rotors" is greatly increased (Barry, 1981, p.64) in such situations. These may occur as lee eddies, or as "bolsters" at the foot of steep windward slopes (Scorer, 1955, in Barry, 1981, p.64. See Figure 1.9). Such turbulence has a significant if poorly understood effect on the pattern of snow transport from windward to leeward locations. However, while turbulence caused by slope breaks may extend for considerable distances (as indicated in Figure 1.9b and c), it was noted in the literature review that blowing snow processes themselves are very localized in extent; a horizontal distance of 100 m (Kotlyakov and Plam, 1966) to 200 m (Föhn, 1980) on both sides of a ridge crest usually contains most blowing snow processes caused by the ridge. In rare cases this distance may be as much as 500 m (Kotlyakov and Plam, 1966).

While the above generalizations about wind transport of snow in rugged terrain have not been investigated before in Kananaskis Country, similar albeit qualitative observations were made in the study areas during the course of this research. In the Fortress Mountain area (Mount Inflexible #3 avalanche path), lee eddies or rotors resembling those in Figure 1.9c were observed on numerous occasions (Plate 1.3). At Highwood Pass, such spectacular lee eddies were not observed; however, considering the orientation and steepness of the ridge on which the avalanche slope was located, and the direction of prevailing winds (see Chapter 2), such situations were very likely. The source of wind-transported snow on lee slopes was often observed to be from immediately adjacent windward slopes (Plate 1.2), illustrating also the localized nature of blowing snow



a Separation at a cliff top (S), joining at J. A 'bolster' eddy resulting from flow divergence is shown at the base of the steep windward slope;

b Separation on a lee slope with a valley eddy. The upper flow is unaffected;

c Separation with a small lee slope eddy. A deep broad valley may cause the air to sink resulting in cloud dissipation above it

Source: *Scorer (1978, in Barry, 1981)*

Figure 1.9 Wind flow separation from slope breaks

processes.

1.6.3 Temperature

Mean annual temperatures in the study area range from -2.0°C to 1.1°C (Table 1.3), with lower values found at high elevation stations (Highwood Pass -2.0°C; Twin One -0.9°C). Warmer mean annual temperatures are associated with valley bottom stations such as Confluence 5 (at 1770 m in the Marmot Creek watershed [Figure 1.3]; -0.4°C) and Kananaskis-Pocaterra (1.1°C).

Mean winter (October-April) temperatures range from -7.8°C (Highwood Pass) to -4.4°C (Kananaskis-Pocaterra). The coolest month tends to be January, when average daily temperatures range from -12.6°C (Confluence 5) to -8.9°C (Kananaskis-Pocaterra) (Table 1.3). However, at Highwood Pass the coldest temperatures occur in December (-12.9°C; Table 1.3).

Air temperatures above 0°C are common in all winter months (Smith, 1979) and are the result of chinook conditions (Longley, 1967). These are responsible for dramatic temperature fluctuations such as occurred in December 1968, when a 42.2°C range in daily maximum temperatures was recorded (McPherson *et al*, 1983).

The extreme variability in winter temperatures in the study area is exemplified not only by the warm chinook conditions but also by the common occurrence of brief periods of extremely low temperatures. These are produced by the incursion and stagnation of very cold continental polar air (Koeppe, 1931, in Smith, 1979). The extreme minimum recorded at Highwood Pass on December 29, 1968 (-44.4°C) was the product of this type of airmass (McPherson *et al*, 1983).

1.7 Avalanche Paths

The Mount Inflexible #3 and Highwood Pass avalanche paths were chosen as study areas because they are relatively accessible and because both affect a transportation route. Dendrochronological studies by McPherson *et al* (1983) also indicate both paths to be active during the avalanche season.

Mount Inflexible #3 is a northeast-facing path located on the scarp slope of the Kananaskis Range (Figure 1.2). It descends 870 m vertically from the 2620 m crest of the

Table 1.3 Mean monthly temperature

	Twin One (1969-1979) °C	Highwood Pass (1966-1973) °C	Kananaskis-Pocaterra (1976-1982) °C	Confluence 5 (1963-1979) °C
January	-12.2	-11.5	-8.9	-12.6
February	-9.4	-9.2	-7.9	-8.8
March	-4.6	-8.1	-4.4	-6.4
April	-2.2	-4.7	-0.6	-6.8
May	1.7	1.9	4.9	3.8
June	6.4	6.0	9.4	8.5
July	9.6	9.0	11.8	11.8
August	8.3	10.6	11.2	10.1
September	5.8	4.0	6.8	8.3
October	0.6	-1.4	3.2	2.8
November	-5.3	-6.9	-5.6	-6.1
December	-8.7	-12.9	-8.3	-8.8
Mean	-0.9	-2.0	1.1	-0.4

Source: McPherson et al (1983)

range to below the Fortress Mountain ski area road, 3.5 km from the junction with Highway 40. The name employed for the path is consistent with the avalanche path inventory carried out by McPherson *et al* (1983). Though the path has a general northeasterly aspect its shallow bowl shape results in smaller scale aspects ranging from north to southeast (Figure 1.10 and Plate 1.4).

The starting zone of Mount Inflexible #3 is composed of a steep (50° to 55°) rock headwall. Because its angle lies outside the usual range assigned to dangerous slab formation (Mellor, 1968; de Quervain, 1975; LaChapelle and Armstrong, 1976; Perla and Martinelli, 1976; Stethem and Perla, 1980) it can only accumulate limited depths of snow, and thus most avalanches in 1982-83 were observed to release in its lower reaches. The abrupt break in slope at 2220 m between the headwall and the talus fan below marks the upper boundary of the track zone. The 32° steep upper section of this hourglass shaped fan contains the upper track. The short midtrack section of the path is located at the constriction in the fan at 2130 m. The lower track and runout zone are not clearly separated although the boundary seems to lie somewhere along the lower reaches of the talus fan. The lower track and runout have slope angles of 25° and about 10° respectively, with the latter extending 100 m horizontally past the ski area road at the northwest margin of the path. The time-lapse system photographed the entire path, with the exception of the upper starting zone.

Timberline at the Mount Inflexible #3 path is located approximately at the midtrack level. The runout zone is dominated by immature Engelmann Spruce and Subalpine Fir, in association with Barratt's Willow and Grey Leaf Willow in mesic and moist locations. All display extensive damage by avalanche activity, although isolated stands of more mature timber are found where the frequency of disturbance is lower. The lower track is dominated by krummholz vegetation (crippled forms of Engelmann Spruce and Subalpine Fir), with sedges, forbs and bare rock becoming increasingly dominant higher up. The middle and upper track sections, subject to an increased frequency of avalanche activity, are composed primarily of unvegetated rock debris with the exception of a small island of krummholz in the upper track.

The second avalanche path is located in Kananaskis Provincial Park directly above Highway 40 at Highwood Pass (Figure 1.2). The unconfined nature of this path actually

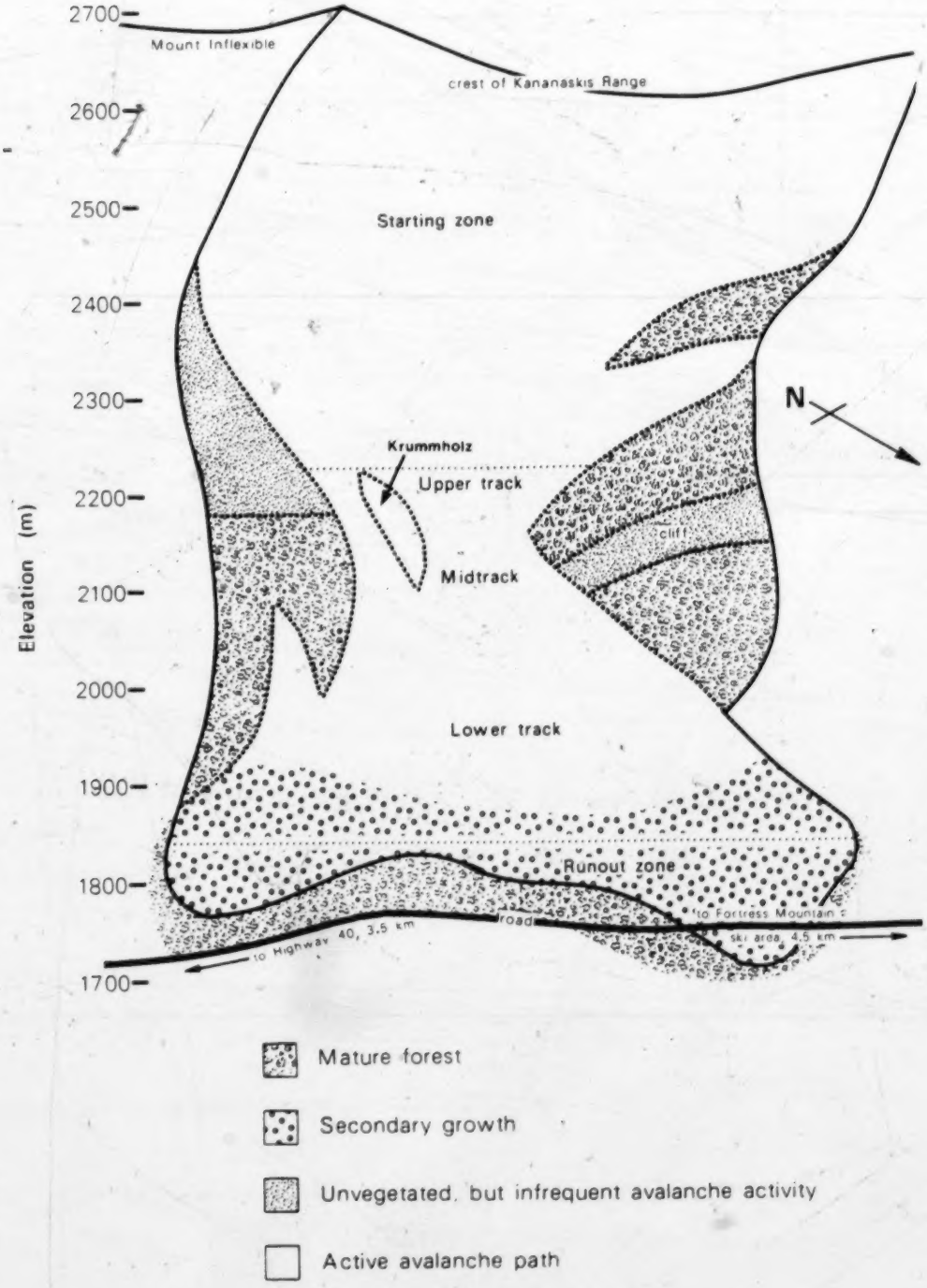


Figure 1.10 Mount Inflexible #3 avalanche path

Plate 1.4 View southwest toward the "Mount Inflexible #3" avalanche path (middle). The Fortress Mountain ski area road is visible at the bottom of the photo.

Photo courtesy of H. McPherson

makes it indistinguishable from a broad avalanche slope on the southwest side of the pass, and thus it was not specifically identified by McPherson *et al* (1983) in their inventory. The top of the starting zone is located at the crest of a distinctive ridge paralleling the Elk Range, at an elevation of 2730 m. The entire path has a total vertical drop of 520 m, and a consistent northeasterly aspect (Figure 1.11 and Plates 1.5 and 1.6).

The starting zone, with a vertical drop of 170 m, consists of bedrock and colluvium at a slope angle of 37°, which is ideal for hazardous slab formation. The upper track section, with a drop of 200 m, has a slope angle of 35°. A distinct bench angled at 25°, between 2360 m and 2310 m, forms the short midtrack section of the path. Almost 95% of all recorded avalanches terminated in this section of lower gradient. Below this bench the slope angle again increases to about 30° to form the lower track, which has a vertical drop of 95 m. The runout zone has a slope angle varying from 12° at its upper end to 0° at Highway 40, and drops only 7 m.

The starting zone and portions of the upper track along the entire avalanche slope at Highwood Pass contain numerous shallow gullies and depressions that function as efficient snow catchments (Plate 1.5). Their efficiency is enhanced by prevailing northwesterly winds which blow across the slope. The slope becomes increasingly dissected by these depressions further to the southeast. On the section monitored by time-lapse photography two broader but nevertheless distinct depressions form the upper track and a portion of the starting zone. Almost every recorded avalanche released and flowed in these shallow channels. An 8 m high rock band with a slope angle of 60° bisects the upper track and serves to locally steepen the gradient and initiate several avalanches.

Timberline is situated at approximately 2290 m at Highwood Pass, and bisects the avalanche slope at the lower track level. Because of frequent avalanche activity on northeast-facing slopes in the pass, however, and the subsequent depression of timberline (Trottier, 1972. See Plate 1.7), its exact elevation is difficult to ascertain. Krummholz vegetation dominates the path up to the midtrack level, and even to the upper track level on higher ground between depressions. Mesic and moist sites in the lower track support low-lying forms of Barratt's Willow and Grey Leaf Willow. All show extensive damage from avalanche activity. The nearly level runout is characterized by a deep snow plant community dominated by Mountain Heath (*Phyllodoce*), White Heather

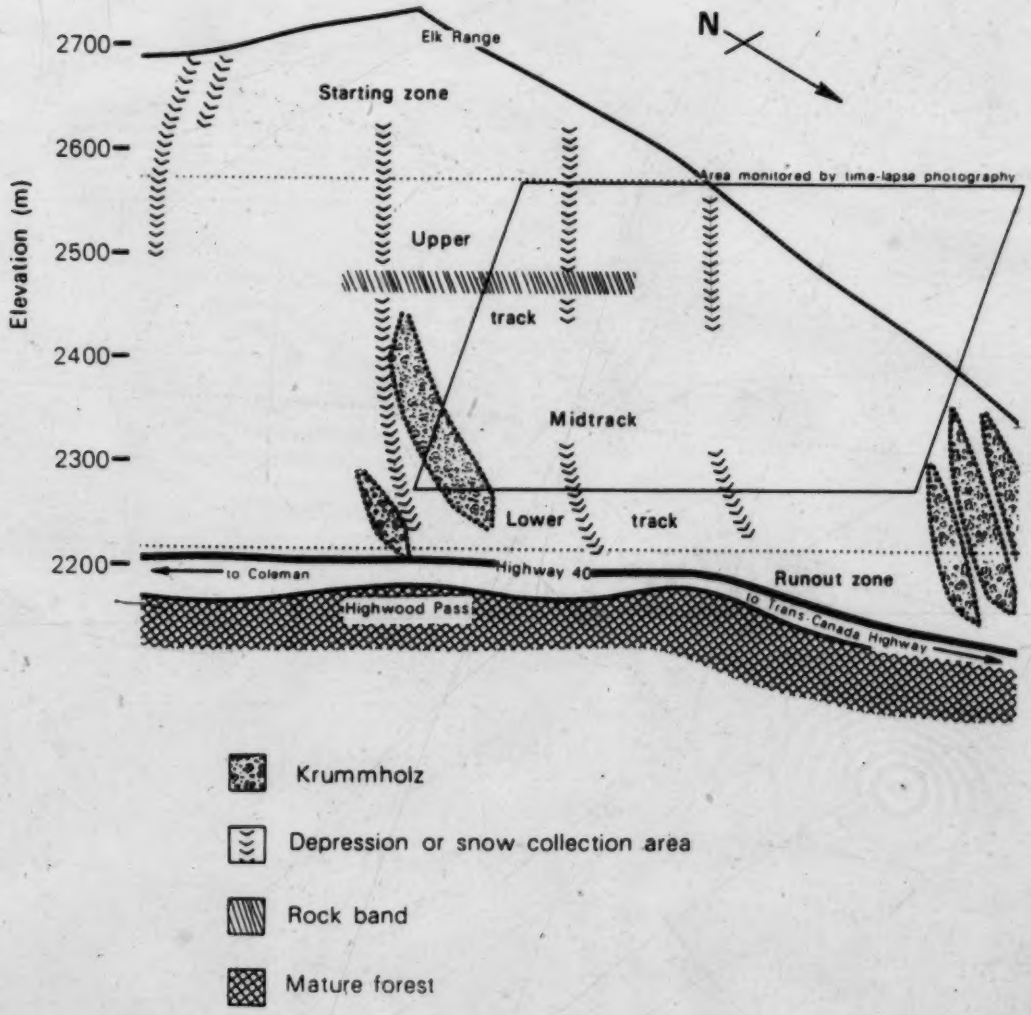


Figure 1.11 Highwood Pass avalanche slope

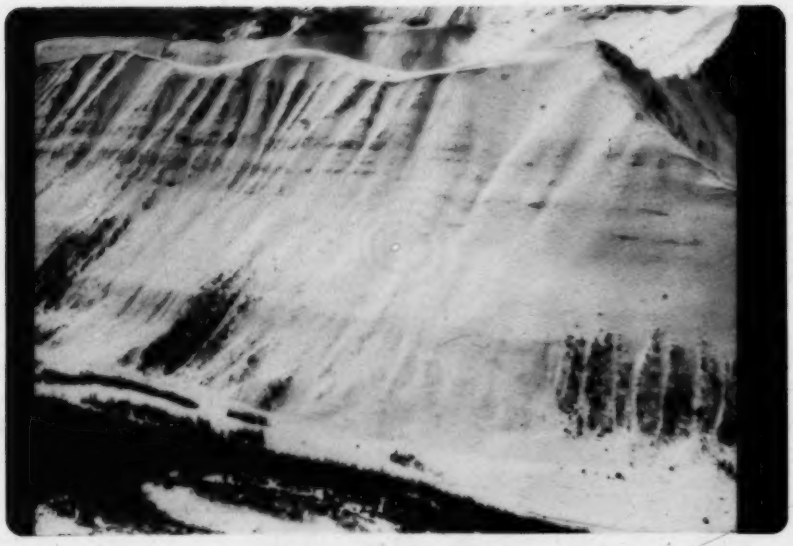


Plate 1.5 View southeast toward the Highwood Pass avalanche slope. Highway 40 is visible at the bottom of the slope.

Photo courtesy of H. McPherson

Plate 1.6 Highwood Pass avalanche slope. Looking to Highway 40, Highwood Pass and the camera site (arrow) from the starting zone. Photo taken in late June, 1984.

Plate 1.7 Recent avalanche damage at Highwood Pass. Highway 40 is in the background.

and sedges (Trottier, 1972). The bulk of the upper track and the entire starting zone support only a sparse association of sedges and forbs.

Kananaskis Provincial Park policy at present time keeps Highway 40 during the winter unplowed south of the Kananaskis Lakes turnoff. Therefore the Highwood Pass avalanche slope could only be reached by snowmobile.

In addition to the two study areas, other avalanche paths were observed occasionally for evidence of avalanche activity. Two which produced high magnitude avalanches are situated on the southwest-facing flank of the Misty Range, crossing Highway 40 between Elbow Summit and Highwood Pass (Figure 1.2). McPherson *et al* (1983) identify these paths as Highwood Pass #2 and #5. Even though a complete record of avalanche activity for 1982-83 is not available for them, they are described here because they supplement the time-lapse record in Highwood Pass.

Highwood Pass #2 falls 838 m vertically to Highway 40, at 2015 m, and is a prime example of a confined avalanche path (Plate 1.8). The starting zone, at 2835 m elevation and with a slope angle of 32°, is characterized by smooth, bare rock surfaces which contribute significantly to snowpack instability (Steel, 1982 ["de Bono" path]; McPherson *et al*, 1983). Smith (1981, in Steel, 1982) has observed high magnitude avalanching on the path every winter in recent years. The runout zone at present extends approximately 100 m beyond the highway almost to Pocaterra Creek.

Highwood Pass #5, also a confined path, falls 700 m to Highway 40, at 2095 m (Plate 1.9). The starting zone, at 2775 m elevation and with a slope angle of 40°, is characterized by bare rock surfaces which again provide minimal anchoring for snow. The runout zone hosts a community of immature Engelmann Spruce, Subalpine Fir and species of willows which displays abundant evidence of disturbance by avalanche activity. Plate 1.9 illustrates clearly the extension of the runout beyond the highway and almost into Pocaterra Creek.

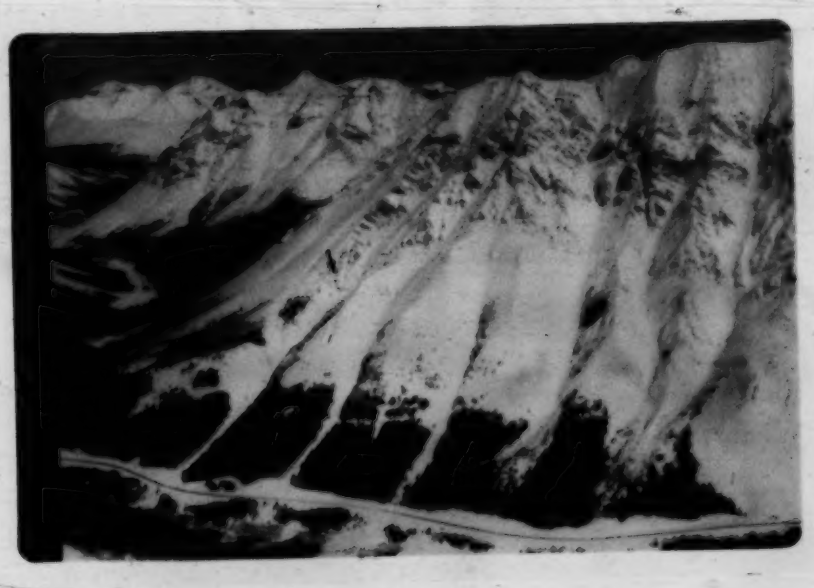


Plate 1.8 View northeast toward the "Highwood Pass #2" avalanche path (far left gully). Highway 40 is visible at the bottom of the photo.

Photo courtesy of H. McPherson

Plate 1.9 View northeast toward the "Highwood Pass #5" avalanche path (right). Highway 40 is visible at the bottom of the photo.

Photo courtesy of H. McPherson

1.8 Research Methodology

The research methodology over the winter of 1982-83 was divided into two main avenues; the time-lapse monitoring of the two avalanche paths, and the collection of detailed weather and snowpack data in the study areas. It was hoped that the time-lapse photography systems would provide valuable information on the frequency, type, size, mode of failure and distance of travel of avalanches, as well as on their relation to weather events and changes in snowpack structure. The systems operated from early January until mid-June on both avalanche paths, and provided continuous records for this period. These records were also supplemented by personal avalanche observations during visits to the study areas.

Weather data were collected over the entire winter in both study areas, from mid-December until mid-June at the Mount Inflexible #3 avalanche path, and from early November until mid-June at Highwood Pass. The data were obtained from recording instrumentation as well as from personal observations during visits to the study areas, and were used for compiling a general weather picture for the winter of 1982-83, as well as for examining more closely their relationship with avalanche formation.

Information on snowpack structure was collected in both study areas contemporaneously with the weather observations. Data were obtained primarily from the observation of snowpit walls, and were used to examine the pattern of snowpack instability over the winter as well as the role of snowpack structure in avalanche formation.

2. WEATHER, WINTER 1982-83

2.1 Weather Observations

Detailed weather data were collected every two weeks at the study areas in order to obtain complete records for the winter of 1982-83. Study sites were utilized for this purpose in order to obtain information which represented conditions on the avalanche paths. Several authors (e.g. Schaerer, 1962; Gardner and Judson, 1970; Martinelli, 1971; Armstrong and Ives, 1976; Perla and Martinelli, 1976; Canadian Avalanche Committee, 1981) have described the various requirements of such a study site. In the siting of these Gardner and Judson (1970) note that exposure, elevation, snow loading characteristics and relation to timbered areas are important considerations. In addition, the study site must be sheltered (to exclude wind effects not present in the avalanche path starting zone), large enough so that tree branches will not affect snowfall at the site, and clear of low brush which would interfere with the lower layers of the snowpack. However, Perla and Martinelli (1976, p.17) concede that realistically its location is ultimately "a compromise between accessibility, shelter efficiency, and ability to provide meaningful data for avalanche slopes".

In view of the above requirements the best location for a study site representing conditions on the Mount Inflexible #3 path was determined to be immediately below the 'Friar's Tuck' and 'Palisade Park' ski runs at the Fortress Mountain ski area (Plate 2.1). The elevation at this location (2090 m) approximately coincides with the lower track section of the avalanche path. The site was subject to some degree of wind drifting as a consequence of the lack of significant timber.

At Highwood Pass the Atmospheric Environment Service climate station site was utilized, as it best fulfilled the requirements outlined earlier and was already in use by Kananaskis Provincial Park rangers as a snow study site. It is located in a sheltered clearing on the west side of Highway 40, directly in the pass at an elevation of 2210 m (Plate 2.2).

Weather observations were carried out following the guidelines set down by the Canadian Avalanche Committee (1981). At the study sites a Lambrecht thermograph housed inside a standard meteorological screen (1.2 m above the snow surface) provided a continuous record of temperature (Plate 2.1). In addition, a maximum / minimum

Plate 2.1 Fortress Mountain study site

Plate 2.2 Highwood Pass study site

thermometer (at the Fortress site only) was employed for checking the accuracy of the thermograph record. A snow board and accumulation stake provided information on new snow amounts and total snowpack depths respectively. Föhn (1977, in Barry, 1981) suggests that the snow board is the only reliable approach to snowfall measurement.

Approximately every two weeks (one week at Highwood Pass) the study sites were visited, the charts changed on the thermographs, and observations made of maximum / minimum temperatures, present temperatures, and the current state of the weather including wind directions and speeds as well as precipitation types and intensities. In addition, new snow depths, total snowpack depths and surface penetration (derived from measurement of foot penetration) were recorded. Stakes were also placed in the upper track sections of the avalanche paths themselves in order to compare snow deposition between the paths and the respective study sites; as discussed later in Chapter 4, the differences between the two at Highwood Pass were quite significant. At Fortress Mountain the differences were not nearly as large.

Measurements of new snow depths were converted to water equivalents in order to facilitate their comparison with each other as well as with other research. The water equivalent of new snow is calculated as

$$HNW = \frac{W}{A} \cdot 10$$

where HNW is the water equivalent in mm, W is the weight of new snow in grams, and A the cross section area of the sampling tube in cm^2.

Appendix 1 illustrates the format employed for recording weather observations. Relative humidity, precipitation gauge data, and 'storm' and 'interval' new snow depths were not recorded because of lack of instrumentation. The specific gravity of new snow was calculated, but did not find any application.

2.2 Results of Weather Observations

2.2.1 Snowfall

Snowfall totals in Kananaskis Country during the winter of 1982-83, as observed at five sites scattered through the region, were generally 10% below the previous five years' average, with light snowfalls associated with chinook cloudiness prevalent (Alberta Recreation and Parks, 1983). Spring was accompanied by heavier snowfalls. Data on monthly snowfall totals from the two study areas, however, present a somewhat more complicated picture.

Monthly snowfall totals for the period from January to April were calculated from snowboard data obtained at the Fortress Mountain and Highwood Pass study sites (Table 2.1). Infrequent storms and associated heavy snowfalls were responsible for a sizable proportion of the monthly totals. The largest totals occurred in April at both study sites, supporting the observation by Janz (1976) and Storr and Golding (1976) that the major proportion of the winter snowfall in the region is received in this month. The large monthly totals in January at both study sites, however, are unusual because this is generally the driest month at higher elevations (Table 1.2).

At Highwood Pass monthly snowfall totals for January, March and April exceeded 1964-75 monthly means, as a result of heavy storm events in each of these months (Table 2.1). The lack of snowfall in February is responsible for the somewhat lower than average total winter snowfall. Information on previous years' snowfall is not available for the Fortress Mountain area, and thus the 1982-83 data could not be compared to long term averages. It is very likely however that the lack of snow in February resulted in a below average winter total. Snowfall totals for each month at Fortress Mountain were appreciably lower than at Highwood Pass, possibly reflecting the higher elevation of the latter and particularly its proximity to the Continental Divide.

2.2.2 Wind

Information on prevailing wind directions during the winter of 1982-83 is based on the time-lapse records, on the periodic weather observations and on cornice build-up. Wind directions could be determined from the time-lapse films by noting the direction of

Table 2.1 Monthly snowfall totals for Fortress Mountain and Highwood Pass, January to April 1983.

Fortress Mountain

	Jan.	Feb.	Mar.	Apr.
Millimetres water equivalent	47	trace	51	73

Highwood Pass

	Jan.	Feb.	Mar.	Apr.
Millimetres water equivalent	99	2	78	104.5

Highwood Pass

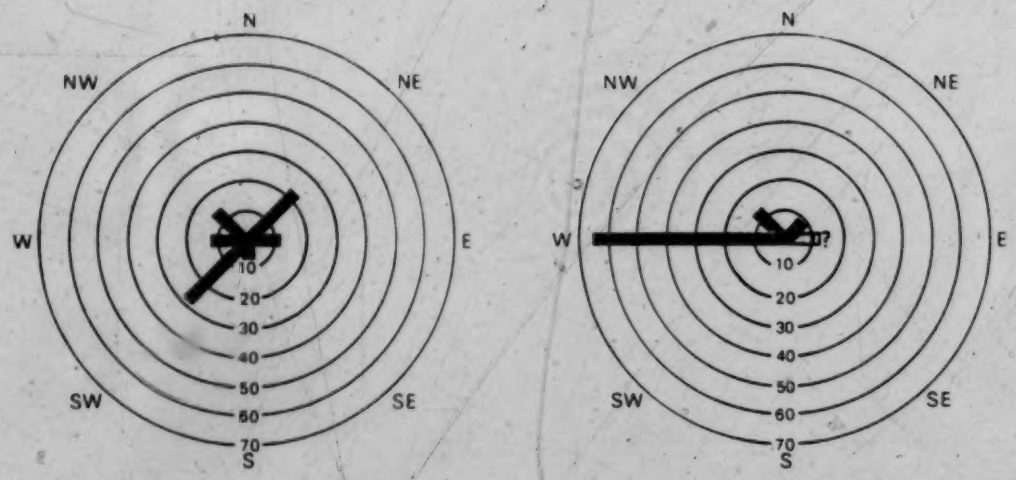
	Jan.	Feb.	Mar.	Apr.
Approximate 1964 - 1975 monthly means; millimetres water equivalent (compiled from unpublished Alberta Forest Service data by Smith, 1979).	85	60	75	95

movement of cloud shadows.

Prevailing winds at Fortress Mountain were from the southwest and northeast, although minor northwesterly, westerly and easterly components were also present (Figure 2.1). During periods of snowfall however almost all winds recorded were southwesterly to northwesterly (Figure 2.2). Several times strong southwesterly winds were observed to be transporting large amounts of snow over the crest of the Kananaskis Range, and onto lee slopes which the Mount Inflexible #3 avalanche path is part of (Plate 1.3). Visits to the study site during these conditions seemed to indicate that such wind loading was not a significant factor there.

At Highwood Pass prevailing westerly winds (Figure 2.1) were often modified to a northwesterly flow through the pass, resulting in cross-slope winds which heavily loaded depressions on the monitored avalanche slope (Plate 1.5). This modification of windflow at ground level became apparent from the fact that almost all upper air movement recorded on the time-lapse films was westerly, whereas 44% of ground observations in the pass (including those obtained during the winter of 1980-81 as well as 1982-83) indicated a northwesterly wind. Cornice build-up in 1982-83, as well as snow drifts remaining in the starting zone of the avalanche slope in June, 1983 supported the westerly component to upper air winds. Northerly and southerly winds were also common in Highwood Pass, accounting for 22% of ground observations each. Since these were not observed above the pass (Figure 2.1), they are probably again westerlies modified at low levels by the orientation of the Pocaterra and Storm Creek drainages. Their effect was also to cross-load depressions on the avalanche slope with snow. Upper air wind directions during snowfall periods were overwhelmingly westerly (Figure 2.2), reflecting the origin of these storms west of the Divide. The winds were, however, modified again at ground level as they blew through Highwood Pass.

Data on wind speeds in 1982-83 were not available for Highwood Pass. These are available for the Fortress Mountain area however (Fortress Mountain Resorts Ltd., 1983; unpublished data) for the period 22 January to 24 April. Observations at the ski area were taken on an exposed ridge, and thus the recorded wind speeds were probably higher than at the study site. The average wind speed for the period of record was 3.9 m s^{-1}, with gust speeds as high as 44.4 m s^{-1} being noted. Calm conditions prevailed 66% of the time.



*Upper air wind observations

Figure 2.1 Frequency in percent of mean daily wind directions; January - May, 1983

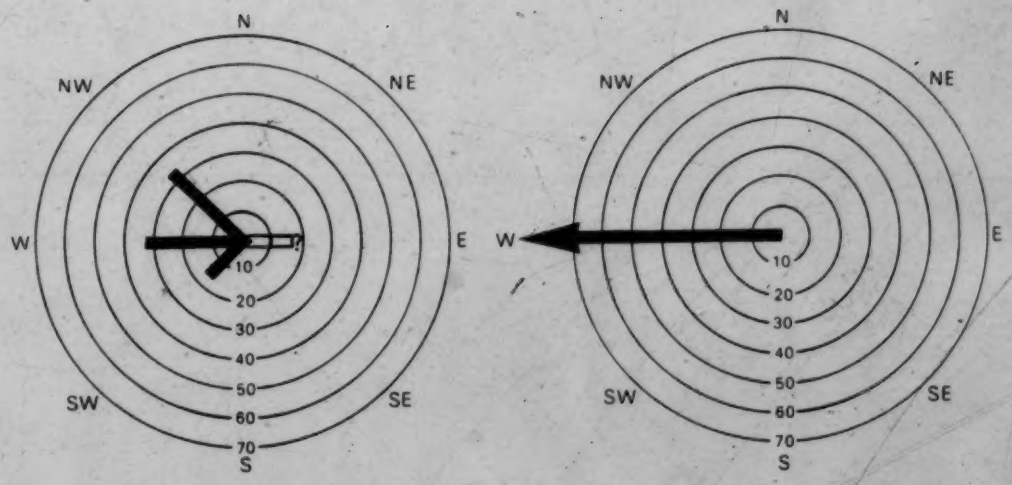


Figure 2.2 Frequency in percent of wind directions during snowfall periods; January - May, 1983

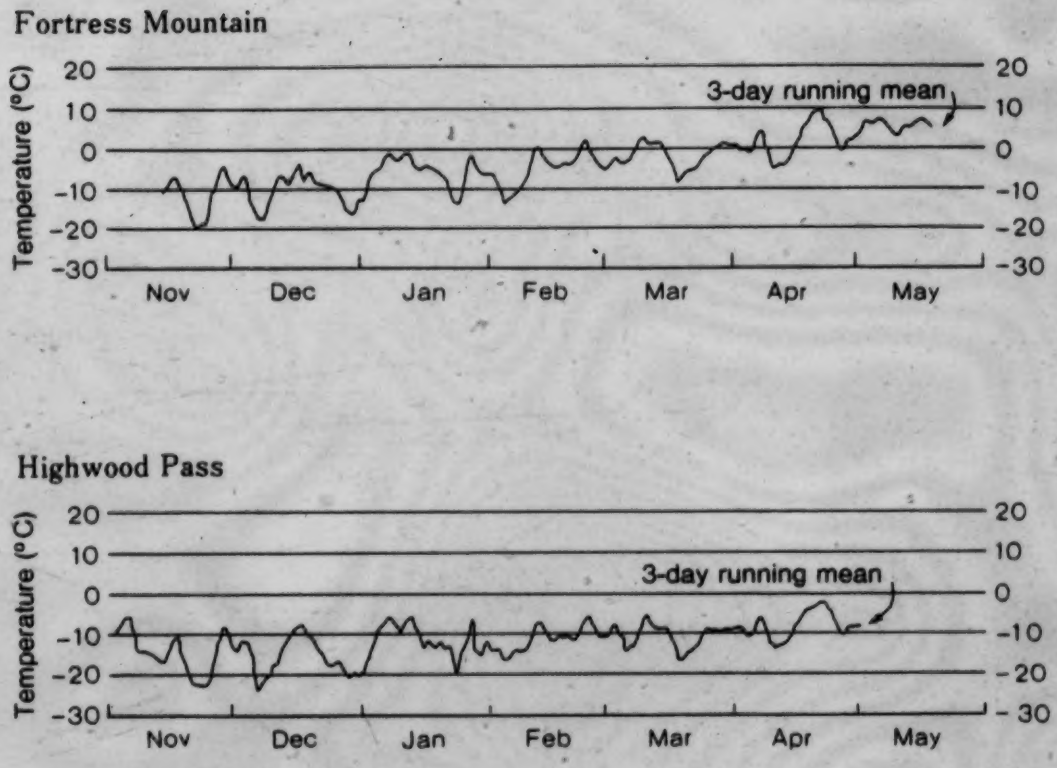
Wind speeds during snowfall periods averaged 2.7 m s^{-1}, with calm conditions occurring 63% of the time.

2.2.3 Temperature

Mean monthly temperatures at Highwood Pass during the winter of 1982-83 were lower than for the period 1966-73 (compiled from unpublished Atmospheric Environment Service data by Smith, 1979). November had a mean temperature of -13.8°C against the seven year average of -6.9°C, and December -15.8°C compared to -12.9°C. Mean January temperatures were average (-11.6°C against a mean of -11.5°C), but then a drop was experienced again as the season progressed (Figure 2.3). February had a mean temperature of -11.6°C against the seven year average of -9.2°C, March -10.8°C against -8.1°C and April -8.3°C against -4.7°C. Detailed data for May 1983 are unavailable but mean daily temperatures rose above 0°C in the middle of the month (recorded by Kananaskis Provincial Park rangers, and some thermograph data which indicated from 17-20 May a mean temperature of 2.6°C); this compares to the 1966-73 mean May temperature of 1.9°C.

Temperatures at Fortress Mountain could not be compared to earlier data. However, in comparison to Highwood Pass, temperatures during the winter of 1982-83 became increasingly warmer as the season progressed, from 2.1°C warmer in November to 9.7°C warmer in April. Mean daily air temperatures at Fortress Mountain rose above 0°C on 27 April (Figure 2.3).

No extreme minimum temperatures were experienced at either Fortress Mountain or Highwood Pass during the winter of 1982-83. The lowest recorded temperatures were -25.0°C at Fortress Mountain and -28.5°C at Highwood Pass.



Highwood Pass sources: *Kananaskis Provincial Park and Atmospheric Environment Service, unpublished data.*

Figure 2.3 Mean daily air temperatures, winter 1982-83

3. TIME-LAPSE PHOTOGRAPHY SYSTEM

3.1 Camera System

A Kodak 'Analyst' Super-8 time-lapse camera with a variable exposure-interval setting (Plate 3.1) was employed to photograph the avalanche path at each study area. A transformer allowed the use of six volt Fulmen generator backup batteries for a power supply instead of the standard penlight cells. The large batteries solved the problem of power loss during periods of very low temperatures.

Both the camera and battery were housed in specially built weatherproof plywood shelters insulated with 10 cm of styrofoam. Space was left for additional insulation which however proved unnecessary. A double glass window was built into the camera shelter in line with the camera lens. Both the camera and battery boxes were covered with tin sheeting, and the cord from the power supply was threaded inside tough 'PVC' tubing. Any remaining exposed wood was treated with a commercial livestock stall protectant, to prevent chewing by rodents, particularly porcupines.

The camera shelter was mounted on a shelf attached to a large tree, approximately 2 m above the ground. The battery shelter sat atop a wooden frame on the ground, which was free-standing to allow raising above the snow (Plate 3.2).

Small quartz clocks ('Micronta' brand) were mounted on wooden booms in front of the cameras. They were positioned so as to be visible in a corner of the film image and thus could provide an accurate temporal record of avalanche activity. The clocks were modified to accept external rechargeable Nickel-Cadmium batteries, which provided much more power in cold weather conditions than the standard penlight cells. Simple weatherproof covers were used on the clocks, since they were exposed to the elements.

Certain points should be kept in mind when setting up such a camera system. The camera must be mounted on a tree which is solid enough not to sway in a strong wind. The camera as well as the battery shelters must be located in such a way that there is no danger of burial by snow. A wind swept site is ideal, although wet snow will adhere to the camera shelter window if it is allowed to face the wind. A camera situated very close to the avalanche path margin must be protected from the windblast of large avalanches. The risk and extent of windblast damage can usually be ascertained from the examination of

Plate 3.1 Kodak "Analyst" Super-8 time-lapse camera

Plate 3.2 Time-lapse monitoring system

vegetation at the path margin or trimline.

The camera system photographing the Mount Inflexible #3 avalanche path was located approximately 750 m from the path. The site was directly accessible by vehicle on the Fortress Mountain ski area road. Although a camera location closer to the avalanche path would have produced a better record of low magnitude avalanches, the site employed in 1982-83 allowed the entire path to be monitored. The camera system at Highwood Pass was located 500 m and on the other side of Highway 40 from the monitored avalanche slope. Being closer to the slope, it produced a better record of small avalanches and sluffs[1].

The exposure interval employed for the photography was eight minutes (i.e. one frame exposed every eight minutes). This permitted a 15 m cartridge of Super-8 ('Kodachrome') movie film to last three weeks. The film was changed every two weeks, which left a one-week margin in case the camera site could not be reached. The camera and clock batteries were also recharged every two weeks, necessitating the use of four of each type of battery. During milder spring weather both systems operated for a month without recharging.

Each cartridge of film was viewed and each frame analyzed using a Super-8 movie projector. For this purpose a remote control mechanism to allow individual frame advance is essential.

Because the time-lapse cameras continued to expose frames even at night, a large part of each film was wasted. This could have been prevented, and the length of time between film changes extended, by the use of a photo cell between the power supply and camera, but it was felt that it was not worth the added effort and expense.

3.1.1 Results

After five and one-half months of operation in the field the time-lapse monitoring systems yielded excellent results. During the study a number of constraints to the technique were also discovered. Perhaps most significantly, the eight-minute exposure interval did not permit the filming of actual avalanche release sequences. Rather, evidence for their occurrence was obtained from the presence of avalanche debris and other tonal

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[1]Small (size 1) avalanches, which often stabilize a slope before dangerous masses of snow build up.

changes in the path. These changes usually took the form of a flicker as an avalanche left a disturbed snow surface in its wake.

Another problem was immediately apparent from the first set of developed films. On both avalanche paths evidence of activity was only visible when the slope was in direct sunlight. The Highwood Pass slope went into shade at approximately 1300 hours (depending on the time of winter) and Mount Inflexible #3 somewhat later, after which snow detail became very difficult to discern. Thus, the use of this technique to monitor steep north-facing slopes in midwinter could pose a problem. Placement of the cameras closer to the avalanche path would alleviate this somewhat, but would result in a much smaller area of the path that can be monitored.

The angle of the sun's rays striking the avalanche path was also critical. Low angle rays tended to produce significantly more pronounced differences in detail between avalanche debris and an undisturbed snow surface as a result of shadows. Very few tonal differences were visible when insolation struck the path at high angles. With regard to snow surface detail, wet avalanche debris showed up much more prominently than dry debris as a result of the low albedo of wet snow.

The recording of two genetically different types of avalanches, which together accounted for nearly all of the releases observed, met with varying degrees of success. An exact time of occurrence was difficult to establish for snowfall triggered avalanches because they usually released during periods of low visibility. Evidence of their occurrence was visible after the storm, usually in the form of avalanche debris. However, even a light snowfall obliterated most of this evidence, which sometimes made accurate determination of the size and extent of the avalanche difficult. The avalanche debris also could not indicate whether more than one release had taken place. When the path was not obscured, the movement of cloud shadows across it was easily confused with avalanching. Thaw triggered wet snow avalanches on the other hand, which were predominant in the period from March to May, were easily identified on the films. With clear sunny conditions a requisite for this type of avalanching the time of occurence could be pinpointed to within a minute if desired. In some of the more dramatic avalanche events the film from one frame to the next records the change from an undisturbed path to one choked with debris (Plate 3.3).

1000 h

1400 h

Plate 3.3 Time-lapse record of wet snow avalanches. 21 April 1983 on the "Mount Inflexible #3" avalanche path.

A distinction between loose snow avalanches and slab avalanches could not be made in most cases from the films, as a result of the distance from the camera to the path. Information on the type of failure was provided primarily by field investigation after the event. However, at Highwood Pass the relative proximity of the camera to the path allowed the mode of failure of several releases to be identified.

The time-lapse record also provided information on weather events. The most useful was the recording of snowfall periods, primarily from the buildup of snow on the clock and trees visible on the film. This information could then be used to establish when the snowfall recorded at the study site fell. Comparisons with Fortress Mountain ski area snowfall records show this method to be quite accurate. However, very light dustings were not recorded by the filming technique (these were at any rate insignificant to avalanche formation).

As noted in Chapter 2, a scarcity of wind data in the study area was partly overcome by determination of approximate wind directions from the time-lapse films. This was primarily achieved by observation of the movement of cloud shadows. Periods of warm weather following snowfalls were also readily identifiable by the melting of snow from various objects in the film image.

The powerful batteries as well as heavily insulated shelters that were utilized proved to be more than adequate in the conditions encountered. However, one aspect of cold weather operation, which cannot be readily solved, was the formation of frost on the windows of the camera shelters. This usually did not persist for long however, and only occasionally hampered the monitoring of the avalanche paths.

3.2 Supplementary Avalanche Observations

Avalanche observations were carried out during the biweekly visits to the study areas in order to verify and supplement the time-lapse records. The detailed guidelines of the Canadian Avalanche Committee (1981) were employed for this purpose.

The observations included the date of release (if known), the path on which it occurred, the size of the avalanche (see Appendix 1) and the approximate number of releases if it was a multiple event, the moisture characteristics of the avalanche debris (wet or dry), the starting and stopping points of the avalanche, its release characteristics;

whether it was a loose snow or slab release and whether it flowed along the ground surface (full depth) or only incorporated surface layers of snow, and the size of the avalanche deposit. Ancillary information such as the thickness and length of a slab fracture face was occasionally available.

The hazardous nature of the avalanche paths under observation as well as the fact that the majority of releases did not reach the runout zone made accurate determination of the nature of the debris difficult. Only on the Highwood Pass #2 and #5 paths, where avalanches terminated close to or on the highway, could debris be closely inspected.

Observations of avalanche damage were unprofitable; the absence of human activity and structures on or near the avalanche paths resulted in damage being confined to small amounts of immature timber and to the snow measuring stakes which had been placed on the paths. The method of triggering of the avalanches was likewise not recorded, because although several types of artificial triggers are outlined by the Canadian Avalanche Committee (1981), all avalanches recorded were naturally triggered by weather.

3.3 Types of Avalanches

Table 3.1 presents the characteristics of every avalanche recorded on the Mount Inflexible #3 path and at Highwood Pass in 1982-83 (observations of avalanche activity on selected other paths are also included). It illustrates the large number of avalanches that occurred on both of the paths in 1982-83. Even if only one avalanche is assigned to situations where more than one is observed to have occurred but the exact number could not be determined, Mount Inflexible #3 still experienced twenty-nine avalanche events, all of which were size 2 or larger (see Appendix 1). Using the same criterion for the Highwood Pass slope, twenty-one avalanche events were recorded, eighteen of which were size 2 or larger.

Although avalanche classifications have identified a number of different types of avalanches (see Fukui, 1966; de Quervain *et al*, 1973; de Quervain, 1975; Perla and Martinelli, 1976), only three types were recorded during the winter of 1982-83. These were wet snow, soft slab and dry, loose snow avalanches. Figure 3.1 illustrates their relative importance. The numbers are not entirely accurate because in many cases the total number of avalanches that released during a storm could not be determined.

Table 3.1 Summary of avalanche activity at Fortress Mountain ("Mount Inflexible #3" path) and Highwood Pass area, winter 1982-83.

DATE	PATH	SIZE*	MOISTURE CONTENT	TYPE	POSITION OF SLIDING (BED) SURFACE	LOCATION ON PATH (START TO FINISH)	WEATHER -W.E.-WATER EQUIVALENT	COMMENTS
16/12/82	Mount Inflexible #3	2	dry	slab	surface layers	upper track	heavy wind loading, temp. max. 0°C	
9-10/1/83	Highwood Pass	2-3	dry	slab	surface layers	starting zone → midtrack	67 mm W.E. snow, west wind	- several releases, crowns visible
9-10/1/83	Highwood Pass #5	3	dry	slab	surface layers	reached runout	67 mm W.E. snow	- deposited onto highway
10/1/83	Mount Inflexible #3	2-3	dry	loose	surface layers	starting zone → midtrack	22 mm W.E. snow	- several releases
23-24/1/83	Highwood Pass	3	dry	slab	surface layers	starting zone → runout	23 mm W.E. snow, west wind	
24/1/83	Highwood Pass	2	dry	slab	surface layers	starting zone → midtrack	23 mm W.E. snow, west wind	
27/1/83	Mount Inflexible #3	2	dry?	slab	surface layers	starting zone → upper track	6 mm W.E. snow and wind loading, temp. max. +2 °C	- 3 releases

* Classification of the Canadian Avalanche Committee (1981).

Continued ...

DATE	PATH	SIZE*	MOISTURE CONTENT	TYPE	POSITION OF SLIDING (BED) SURFACE	LOCATION ON PATH (START TO FINISH)	WEATHER -W.E.=WATER EQUIVALENT	COMMENTS
13/2/83	Mount Inflexible #3	3/4	moist	?	surface layers	upper track → mid/lower track	temp. max. +0.5°C, higher previously	- more than one release
28/2-1/3/83	Mount Inflexible #3	2	dry	slab?	surface layers	starting zone → upper track	27 mm W.E.snow, west wind	- new snow slid on melt-freeze crust
9/3/83	Mount Inflexible #3	3	wet	loose	surface layers	upper track → mid/lower track	temp. max. +8.5°C	
9/3/83	Highwood Pass	2	wet	loose	surface layers	starting zone → midtrack	temp. max. 0°C	- path heavily loaded from 45.5 mm W.E. snow on 1-2 March
20-21/3/83	Mount Inflexible #3	1-2	moist	?	surface layers	upper/midtrack	18 mm W.E. snow, temp. max. 0°C	- slid on 2 cm graupel
22/3/83	Mount Inflexible #3	2	moist	loose	surface layers	midtrack	temp. max. - 0.5°C	- slid on 2 cm graupel
24/3/83	Mount Inflexible #3	2-3	wet	slab?	surface layers	midtrack → lower track	6 mm W.E. snow, temp. max. 0°C	
between 16 and 25/3/83	Highwood Pass	1	dry	loose	surface layers	starting zone → upper track	up to 32.5 mm W.E. snow, west wind	- numerous releases. Cornices indicate winds during storm

Continued ...

DATE	PATH	SIZE*	MOISTURE CONTENT	TYPE	POSITION OF SLIDING (BED) SURFACE	LOCATION ON PATH (START TO FINISH)	WEATHER -W.E.=WATER EQUIVALENT	COMMENTS
28/3/83	Highwood Pass	2	dry	loose	surface layers	starting zone → midtrack	32.5 mm W.E. snow 16-25 March, west wind	- though study site temperatures reached only -7°C, the path was in direct sunlight. Cornices indicate winds during storm
3-4/4/83	Highwood Pass - all paths with NE aspect.	2-3	dry	slab	surface layers	starting zone → runout	45.5 mm W.E. snow	- several releases. Cornices indicate winds during storm.
5/4/83	Highwood Pass	1	moist	loose	surface layers	upper track	45.5 mm W.E. snow on 3-4 April	- though study site temperatures reached only -4°C, the path was in direct sunlight
6/4/83	Highwood Pass #5	3/4	wet	slab	surface layers	starting zone → lower track	45.5 mm W.E. snow and heating	- stopped 100 m above highway
6/4/83	Highwood Pass	1-2	wet	loose	surface layers	upper track	45.5 mm W.E. snow, temp. max. +4.5°C	- two releases. Numerous others on slopes with S-SW aspect in Highwood area.
6/4/83	Mount Inflexible #3	3	wet	?	surface layers	upper track → midtrack	23 mm W.E. snow on 2-3 April, temp. max. +13.5 on 6 April	

Continued ...

DATE	PATH	SIZE*	MOISTURE CONTENT	TYPE	POSITION OF SLIDING (BED) SURFACE	LOCATION ON PATH (START TO FINISH)	WEATHER -W.E.=WATER EQUIVALENT	COMMENTS
17/4/83	Highwood Pass	2	wet	?	surface layers	starting zone → upper/midtrack	19 mm W.E. snow on 8-9 April, temp. max. +3.5°C on 17 April	
18/4/83	Mount Inflexible #3	2	wet	?	surface layers	upper track → mid/lower track	temp. max. +13.5°C	- numerous wet releases on slopes of NE aspect in Kananaskis valley near Fortress
18/4/83	Mount Inflexible #3	3	wet	?	surface layers	upper track → lower track	temp. max. +13.5°C	
19/4/83	Mount Inflexible #3	2/3	wet	?	surface layers	upper track → midtrack	temp. max. +14°C	
20/4/83	Mount Inflexible #3	3	wet	?	surface layers	upper track → lower track	temp. max. +16.5°C	
20/4/83	Mount Inflexible #3	2	wet	?	surface layers	upper track → midtrack	temp. max. +16.5°C	
21/4/83	Mount Inflexible #3	2	wet	?	surface layers	starting zone → midtrack	temp. max. +15.5°C	

Continued ...

DATE	PATH	SIZE*	MOISTURE CONTENT	TYPE	POSITION OF SLIDING (BED) SURFACE	LOCATION ON PATH (START TO FINISH)	WEATHER -W.E.=WATER EQUIVALENT	COMMENTS
21/4/83	Path southeast of Mount Inflexible #3	2/3	wet	?	surface layers		temp. max. +15.5°C	
21/4/83	Mount Inflexible #3	3/4	wet	?	surface layers	upper track → lower track	temp. max. +15.5°C	
21/4/83	Mount Inflexible #3	4	wet	?	surface layers	upper track → lower track/runout	temp. max. +15.5°C	
21/4/83	Mount Inflexible #3	3	wet	?	surface layers	upper track → midtrack	temp. max. +15.5°C	
21/4/83	Path northwest of Mount Inflexible #3	3	wet	?	surface layers	reached mid/lower track	temp. max. +15.5°C	
21/4/83	Mount Inflexible #3	3/4	wet	?	surface layers	upper track → mid/lower track	temp. max. +15.5°C	
24-25/4/83	Mount Inflexible #3	3-4	moist	slab	surface layers	reached lower track/runout	50 mm W.E. snow	several releases, crown fracture on NW side of path
24-25/4/83	Path northwest of Mount Inflexible #3	3	moist	slab?	surface layers	reached lower track	50 mm W.E. snow	

Continued ...

DATE	PATH	SIZE*	MOISTURE CONTENT	TYPE	POSITION OF SLIDING (BED) SURFACE	LOCATION ON PATH (START TO FINISH)	WEATHER -W.E.=WATER EQUIVALENT	COMMENTS
24-25/4/83	Highwood Pass	2-3	dry	slab	surface layers	starting zone → midtrack/runout	40 mm W.E. snow, wind	- 3/4 releases
25/4/83	Highwood Pass #2	4	moist	slab	surface layers	reached runout	40 mm W.E. snow, wind?	- crossed and blocked highway
25/4/83	All slopes in Highwood Pass area	2-4	moist	slab	surface layers/ full depth		40 mm W.E. snow, wind	- crown fractures one metre high on east/ northeast slopes
between 29/4 and 3/5/83	Mount Inflexible #3	2-3	wet	?	full depth	upper track → lower track/runout		- temperatures well above freezing
between 29/4 and 3/5/83	Mount Inflexible #3	3	wet	?	full depth	upper track → mid/lower track		- temperatures well above freezing
4/5/83	Mount Inflexible #3	2	wet	?	surface layers	upper track → mid/lower track	temp. max. +8.5°C	
4/5/83	Mount Inflexible #3	3	wet	?	surface layers	upper track → mid/lower track	temp. max. +8.5°C	
5/5/83	Mount Inflexible #3	2	wet	?	surface layers	upper track → mid/lower track	temp. max. +8.5°C	
6/5/83	Highwood Pass	2	wet	?	surface layers	starting zone → midtrack		- temperatures unknown, but maximum above 0°C

Continued ...

DATE	PATH	SIZE*	MOISTURE CONTENT	TYPE	POSITION OF SLIDING (BED) SURFACE	LOCATION ON PATH (START TO FINISH)	WEATHER -W.E.=WATER EQUIVALENT	COMMENTS
8/5/83	Mount Inflexible #3	3	wet	?	full depth	upper track → mid/lower track	temp. max. +7.5°C	
11/5/83	Mount Inflexible #3	2	wet	?	full depth	upper track → mid/lower track	temp. max. +12.5°C	
15/5/83	Highwood Pass	1-2	wet	loose	surface layers	starting zone → upper/midtrack		- approximately 12 releases; temperatures unknown but above 0°C
17/5/83	Highwood Pass	1	wet	loose	surface layers	midtrack	heavy snow, temp. max. +5.0°C	
21/5/83	Highwood Pass	1/2	wet	loose	surface layers	starting zone → upper/midtrack		- temperatures unknown but above 0°C
23/5/83	Highwood Pass	2	wet	loose	surface layers	starting zone → upper/midtrack		- two releases; temperatures unknown but above 0°C
28/5/83	Highwood Pass	2	wet	loose	full depth	starting zone → upper/midtrack		- temperatures unknown but above 0°C - mixed snow-debris release, travelled across bare ground

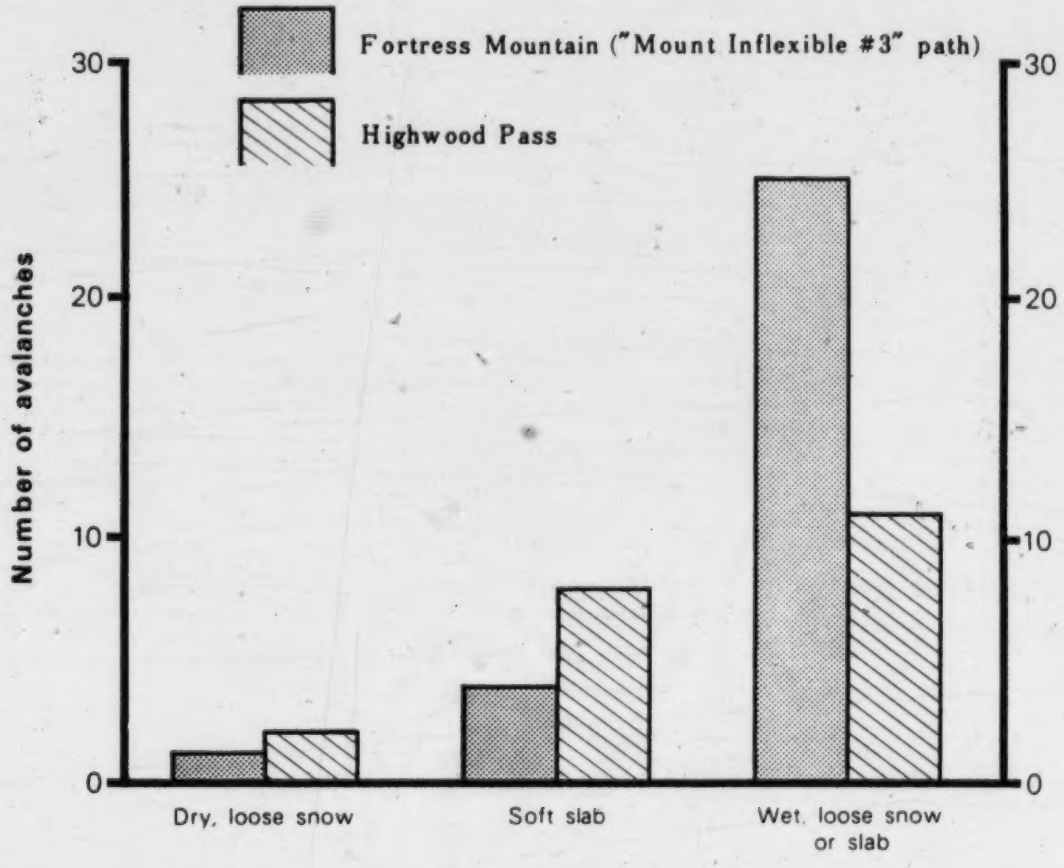

Figure 3.1 Number of avalanches by type, 1982-83

However, the predominance of wet snow and soft slab avalanches is clear, with the former being especially significant in spring (Figure 3.2). Table 3.1 shows wet snow avalanches on the Mount Inflexible #3 path to generally have been larger than soft slab avalanches. In contrast, the slope above Highwood Pass produced larger soft slab avalanches than wet snow ones. Dry, loose snow avalanches were not as significant as the first two types; they were recorded on only three occasions (Figures 3.1 and 3.2), and were relatively small in size.

3.3.1 Wet snow avalanches

Wet snow avalanches are distinguished by flow along the ground rather than by high-speed airborne movement, due to the presence of free water in the released snow (Mellor, 1968). This free water also has the effect of freezing the wet snow by regelation (Perla and Martinelli, 1976) into an extremely hard and impenetrable mass as soon as it ceases to flow.

Days with wet snow avalanches accounted for 83% and 52% of all avalanche days on the Mount Inflexible #3 path and at Highwood Pass respectively. They followed a clear diurnal pattern in response to daytime air temperature maximums (Table 3.1), rather than occurring during or immediately after storms as did dry snow avalanches.

Figure 3.2 shows a peak in wet snow avalanche activity on the Mount Inflexible path in April, with 60% of the winter's total number of such avalanches in this month. The sudden decrease in wet releases in May, to less than half the number of the previous month, is a reflection of the increasingly shallow snowpack as a result of avalanching and ablation.

At Highwood Pass a peak in wet snow avalanche activity does not occur until May (Figure 3.2), when 55% of the winter's total number of wet snow avalanches take place. This is a reflection of the later seasonal warming of temperatures (Figure 2.3) in this study area, and a sufficient depth of snow still on the avalanche slope in May to produce avalanches (Figure 4.2).

The manner of release of wet snow avalanches could generally not be determined, although the time-lapse record at Highwood Pass shows many on that path to be small magnitude slides originating at a point (Table 3.1 and Plate 3.4). However, while wet slab

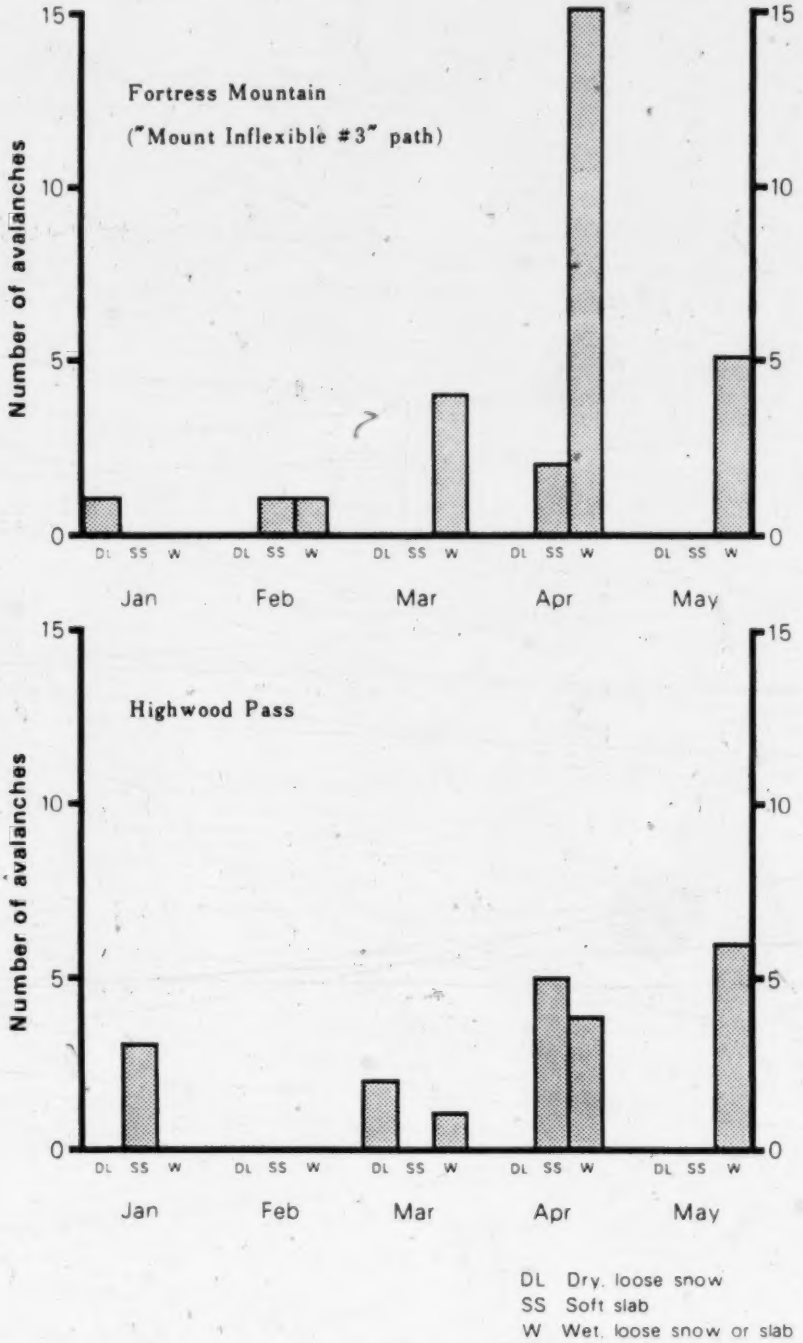

Figure 3.2 Number of avalanches by type and month, 1982-83

Plate 3.4 5 April 1983 sluff at Highwood Pass

releases are usually of a higher magnitude than ones originating at a point (as a result of release over a broader area), wet loose snow avalanches can also attain large size if the destruction of grain bonds has proceeded deep into the snowpack prior to release and large amounts of incohesive snow are incorporated into the moving avalanche (Armstrong, 1976).

3.3.2 Soft slab avalanches

Slab avalanches pose a significant hazard because they "... come as the final collapse of snowmasses built to dangerous proportions under conditions of marginal stability" (Mellor, 1968, p. 19), and release large quantities of energy at failure compared to loose snow avalanches. The sole requirement for slab conditions is sufficient internal cohesion in the snow to transmit tensile stress and permit fracture propagation (Mellor, 1968).

The distinction between soft and hard slab is a subjective one, but the first is usually defined as soft enough to ski through and which quickly disaggregates into an incohesive mass after release (Perla and Martinelli, 1976). Extreme hard slab, on the other hand, cannot be penetrated even by ski edges. Soft slab conditions usually exist when the slab has a density of less than 300 kg m^{-3} and a rammsonde strength of less than 10 kg cm^{-1} (LaChapelle and Armstrong, 1976).

Soft slab is generally felt to be the product of moderate winds and high precipitation intensities at temperatures just below 0°C (Judson, 1967), and can be formed even on windward exposures (LaChapelle, 1967). Early research (Seligman, 1936) had already recognized that soft slab was produced when the amount of precipitation or drifted snow was too great for the wind to pack solidly into hard slab.

Soft slab avalanches were the second most common type of release recorded in 1982-83, occurring in midwinter as well as in spring (Figures 3.1 and 3.2). Although moist snow may have been contained in some of these, they were much drier than wet snow slab avalanches. Three soft slab events were recorded on the Mount Inflexible #3 path (Table 3.1). The event of 24-25 April consisted of several soft slab avalanches, and crown fractures [1] from these were visible more than a week later (Plate 3.5).

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[1]The upper fracture boundary of a released slab (Figure 1.1).

Plate 3.5 "Mount Inflexible #3" avalanche path on 3 May 1983. Crown faces of soft slab avalanches are visible at top right.

Soft slab avalanching was recorded at Highwood Pass on four different occasions (Table 3.1), with all of them consisting of two or more individual avalanches. High magnitude (size 3 to 4) soft slab avalanches also occurred on the Highwood Pass #2 and #5 paths. The most unequivocal proof of soft slab conditions in the Highwood Pass area were the crown fractures produced by the 24-25 April avalanches. These included a one-metre high crown face (Figure 1.1), located across the valley from the Highwood Pass #2 path (Plate 3.6) and another approximately 500 m in length on an east-facing slope in Tyrwhitt Cirque (Figure 1.2 and Plate 3.7).

3.3.3 Dry, loose snow avalanches

Loose snow avalanches occur when the steepness of a slope exceeds the angle of repose of certain types of weak snow (Mellor, 1968; Perla and Martinelli, 1976). A cohesionless mass of snow, usually less than one cubic metre in volume, slips out of place. This either comes to rest at a new angle of repose or imparts enough energy to the snow in its path to cause an avalanche (Perla and Martinelli, 1976). The exact critical angle of repose depends on the temperature, moisture content and shape of the snow grains (Perla and Martinelli, 1976). Loose snow avalanches are generally small compared to slab releases, although very large ones have been known to occur, especially in maritime climates (Mellor, 1968; LaChapelle and Armstrong, 1976; Perla and Martinelli, 1976).

The lack of intergranular cohesion necessary to produce dry, loose snow avalanches is usually the result of wind-free snowfall (Mellor, 1968; LaChapelle and Armstrong, 1976), although the lack of cohesion can also develop by the destruction of intergranular bonding following snow metamorphism (Mellor, 1968).

Dry, loose snow avalanches were the third type of release recorded in 1982-83 (Figure 3.1). These however took place only during two snowfall periods, and were not particularly large. Because of their characteristically small size (Mellor, 1968) however, and the fact that such small avalanches can be difficult to spot even under conditions of perfect visibility (for example, see Plate 3.4), many dry, loose snow avalanches may have escaped detection.

A series of snowfalls from 16 to 25 March at Highwood Pass produced numerous dry, loose snow sluffs, as well as a size 2 avalanche on 28 March. These loose releases

Plate 3.6 One metre high crown face from a 24-25 April 1983 soft slab avalanche, Highwood Pass area. Located on a northeast-facing slope.

Plate 3.7 Extensive soft slab crown face on east-facing slopes of Tyrwhitt Cirque. Photo taken after the 24-25 April 1983 storm.

are somewhat anomalous because a westerly wind was present during the snowfalls, as indicated by cornices after the snowfall (Plate 3.8). On the Mount Inflexible #3 path, a snowfall in the absence of wind on 10 January resulted in a number of dry, loose snow avalanches which were somewhat larger (size 2-3) than the ones at Highwood Pass (Table 3.1).

3.4 Comparison of Avalanche Types With Other Mountain Regions

The types of avalanches recorded in the two study areas in 1982-83 can be compared to those observed in other mountain regions.

The dominance of new snow soft slab avalanches has been observed in many mountain regions, including the Front Ranges of the Colorado Rockies (Judson, 1964; 1967; Martinelli, 1971), the San Juan Mountains of Colorado (Armstrong *et al*, 1974; LaChapelle and Armstrong, 1976), the Swiss Alps (Zingg, 1966) and the Coast Mountains of British Columbia (Stethem and Hetherington, 1978). While they were not the most common type of avalanche in the two Kananaskis Country study areas in 1982-83, they were nevertheless very significant. There is also the earlier mentioned possibility that because of poor visibility during snowfalls, some soft slab avalanches could have escaped detection. Soft slab avalanches are presumably so common in many diverse climates because snowfall is a major factor in avalanche formation (Zingg, 1966; Judson, 1967; de Quervain, 1975; Perla and Martinelli, 1976; Price, 1981; Roch, 1981).

The importance of spring-time wet snow avalanches in the Kananaskis in 1982-83 has also been observed in the San Juan Mountains of Colorado (Armstrong *et al*, 1974; LaChapelle and Armstrong, 1976), although not nearly to the same extent; there they account for 20% of the annual total of avalanches (LaChapelle and Armstrong, 1976), with the majority being composed of loose snow rather than slabs. Judson (1967) notes that at high elevations in the Colorado Front Ranges wet, loose snow avalanches only account for 10% of the annual total. He however concedes that this low figure is partly the result of the constant artificial release of avalanches on the paths studied, which keeps snow depths in them to minimum levels. In Juneau, Alaska wet snow avalanches are the most common type of release (Hutcheon and Lie, 1978), but this is to be expected for an area located directly on the coast.

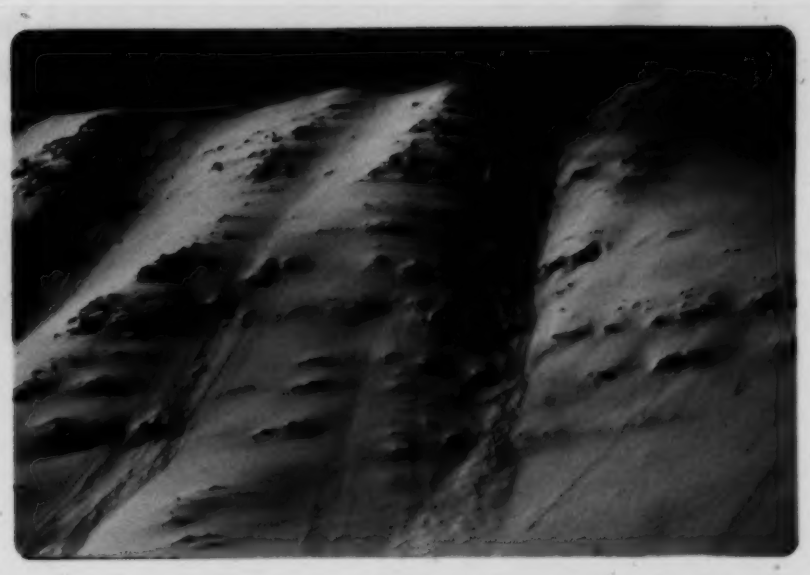


Plate 3.8 Highwood Pass avalanche slope on 25 March 1983. Heavily wind loaded depressions, cornices and loose snow sluffs are visible.

Dry, loose snow avalanches occurring during periods of snowfall account for 20% of the annual total of avalanches in the San Juan Mountains of Colorado (LaChapelle and Armstrong, 1976), and for 16% in the Colorado Front Ranges (Judson, 1967). Although more numerous than those recorded in Kananaskis Country in 1982-83, they are likewise small in size; in the San Juan Mountains almost all are of sluff size (LaChapelle and Armstrong, 1976). As noted earlier, the number of dry, loose snow avalanches in the Kananaskis was probably somewhat higher, because many may have escaped detection due to their small size.

Although the data base is too small to be able to confidently explain the distribution of avalanche types in the study areas in 1982-83, some speculation is possible. Judson (1967) observed in the Front Ranges of the Colorado Rockies that large, dry loose snow avalanches are rare because deep snowfalls are often accompanied by winds which create slabs. If the same situation occurs in Kananaskis Country, it would explain both the relatively large numbers of soft slab avalanches and the small numbers (and sizes) of dry, loose snow avalanches in 1982-83.

The intensity of springtime wet snow avalanching depends greatly on snow accumulation patterns and avalanche activity earlier in the winter, because these determine the amount of snow left on the avalanche path in the spring (Judson, 1967; Armstrong, 1976). The large numbers of wet snow avalanches in 1982-83, especially in the spring, indicate that avalanching earlier in the winter did not remove significant amounts of snow from the avalanche paths. As a result, they still had enough snow on them in the spring to produce extensive avalanche activity.

4. SNOWPACK INSTABILITY, 1982-83

Part of the purpose of this research was to identify latent weaknesses within the snowpack that produced periods of instability during the winter of 1982-83. The importance of snowpack structure in the development of avalanche hazard conditions in a continental climate was emphasized in Chapter 1.

The first half of this chapter deals with the patterns of snowpack development and instability at the study sites over the winter, and the sources of instability. In the second half, the relationship between instability and actual avalanche failures is examined.

4.1 Snowpack Observations

Snow profiles were obtained at the study sites (see Chapter 2) in order to record the stratigraphy of the snowcover and the characteristics of the individual snow layers (Plate 4.1). These data were utilized in two ways:

-to assess the degree of instability present in each of the snow profiles collected over the winter, and make some attempt to identify potential failure planes, and

-to pinpoint failure planes and their characteristics which produced the avalanches recorded by the time-lapse monitoring systems.

Snow pits were dug weekly at Highwood Pass and biweekly at Fortress Mountain, following the guidelines of the Canadian Avalanche Committee (1981). The objectives of observing snow profiles are primarily (Canadian Avalanche Committee, 1981, p.11):

- to identify weak layers and their strength,
- to observe snow temperatures,
- to determine the thickness of a potential slab avalanche, and
- to determine the state of metamorphism of the snow.

Prior to the digging of a snowpit the surface texture of the snowcover was recorded (smooth, wavy, sun cups, rain channels, drifts or sastrugi) which provided evidence of prior wind action, rain or melting. In addition, a 'ram' profile was obtained with a standard Haefeli rammsonde (Bader *et al*, 1939) whenever possible (Plate 4.2). The procedure is described by several authors (e.g. Gardner and Judson, 1970; Perla and Martinelli, 1976; Canadian Avalanche Committee, 1981). Ram hardness is derived from

Plate 4.1 Snowpack data collection; Fortress Mountain study site

Plate 4.2 Obtaining a ram profile; Fortress Mountain study site

the equation

$$R = \left(\frac{n \cdot h \cdot W_H}{\Delta p} + W_T + W_H \right) g$$

where R is the ram hardness in Newtons, n the number of blows of the hammer, h the drop height of the hammer in cm, Δp the increment of penetration for n blows in cm, W_T the mass of the tubes including guide rod in kg, W_H the mass of the hammer in kg and g acceleration due to gravity (the value 10 m s^{-2} is adequate). A hammer of 1 kg mass was generally utilized (two profiles at Highwood Pass were obtained with a 0.5 kg hammer), since a lighter one was not available. Its disadvantage, noted also by other authors (e.g. Perla, 1969; Martinelli, 1970; Stethem and Tweedy, 1981), was its excessive weight, which caused the rammsonde to pass through low density surface snow layers often containing critical failure planes.

The snowpit was used to obtain a temperature profile of the entire snowcover (measurements were taken at 10 cm intervals; at 20 cm intervals below 1.5 m depth) as well as to identify layer boundaries and weak layers or layer interfaces. Provided the layer was thick enough to permit sampling, data on snow hardness, grain type and size, free water content of the snow and specific gravity were obtained (see Appendix 1). Specific gravity is obtained from

$$G = \frac{2W}{1000}$$

where G is the specific gravity and W is the weight of snow in a 500 cm^3 snow sampling tube.

The shovel shear test, as described by the Canadian Avalanche Committee (1981), was used as an additional means of locating potential and actual failure planes in the snowpack. It also indicated the approximate force required to produce failure. The test consisted of excavating a column of snow of given dimensions in the snowpit wall, and then exerting pressure on it in a horizontal direction with a snow shovel until a shear occurred. The depth and character of any shears which were produced were noted on the snow profile.

The time profiles in Appendix 2 contain every snow profile obtained at Fortress Mountain and Highwood Pass in 1982-83. Information on weather conditions at the time

of sampling is included to produce a complete observation record. These time profiles provide a graphic representation of the development of snowpack structure at the study sites over the winter.

4.2 Indices of Snowpack Instability

Several reliable indices are available to the field worker for determining levels of snowpack instability. In combination they present a detailed picture of the strength of individual layers and layer interfaces. The obtaining of these data was dealt with in the previous section: in the next, the contribution of each of these indices to snowpack instability is discussed.

4.2.1 Snowpack depth

The primary requirement for avalanching is a sufficient depth of snow in order that terrain asperities such as brush and boulders are covered to produce a smoothed foundation. Several authors have noted minimum snowpack depths necessary for avalanching. Perla and Martinelli (1976) feel one metre is sufficient on most paths; exact depths vary with detailed terrain configuration and the nature and degree of snowcover instability. On paths devoid of terrain irregularities, such as those on smooth rock, grass or perennial snowfields as little as 15 cm of snow may be sufficient (Perla and Martinelli, 1976). The U.S. Forest Service (1953) believes a minimum snow depth of 60 cm at Alta, Utah (Wasatch Mountains) will produce avalanching. Borland (1954) feels that only 30 cm is necessary at Berthoud and Loveland Passes in the Front Range of the Colorado Rockies. Long term research in the San Juan Mountains of Colorado indicates a mean snowpack depth of 76.3 cm at first 'significant' avalanching (LaChapelle and Armstrong, 1976). At Rogers Pass, British Columbia, Schaerer (1962) notes that a 70 cm snowpack can produce large avalanches that reach the valley.

The amount of snow overlying potential failure planes is, in addition to total snowpack depths, important. Its weight will determine the magnitude of the compressive, shear and tensile stresses acting on these weaknesses. However, critical depths in this regard are nearly impossible to establish, since they greatly depend on the strength of the underlying potential failure planes and the density of the overlying snow.

4.2.2 Snow temperature

Snow temperatures are an important factor in the formation of instability when the snowpack approaches an isothermal condition, usually in the spring. The temperature of the entire snowpack is then critical to the evaluation of wet snow instability (Armstrong, 1976). Armstrong in the San Juan Mountains of Colorado notes that once the entire study site snowpack reaches a temperature of -2.0°C or above, the probability of wet snow avalanches is greatly increased. More insolation is available to the avalanche slopes than the study site, and thus the snowpacks on the slopes reach isothermal conditions earlier. Schaerer (1962), at Rogers Pass in British Columbia, has similarly observed that the initiation of wet snow avalanching coincides with the attainment of isothermal snowpack conditions in the starting zones of the avalanche paths.

The role of subfreezing snow temperatures on snowpack instability is not known. However, bed surface (Figure 1.1) temperatures of slab avalanches in various climates have been analyzed by Perla (1977) and Stethem and Perla (1980). Their results indicate that most bed surfaces have temperatures ranging from -5.0°C to 0°C and that 95% of slab avalanches have bed surface temperatures of -10.0°C or warmer.

4.2.3 Grain type

The primary purpose of examining snow grain types in the snowpit wall is to locate hard and cohesive layers which could act as bed surfaces, or conversely soft and incohesive snow which could fail in shear and possibly act as a lubricating layer (Stethem and Perla's [1980] "Gleitschicht". See Figure 1.1). The contributions of different grain types to snowpack instability were discussed in the literature review.

Some grain types, such as depth hoar, are almost always a source of instability. Others, such as well bonded equi-temperature grains, or melt-freeze grains in a frozen state, are generally associated with significant strength. In reality however the strength of a certain grain type is usually ascertained from its hardness characteristics, and response to mechanical tests such as the rammsonde and shovel shears.

Despite the rule of thumb that larger grain size equates with weaker snow (Perla and Martinelli, 1976), grain diameter is not a useful index of instability ; the size-strength relationship is often nullified by other properties of snow.

4.2.4 Snow density and hardness

Snow density provides a useful index of snowpack instability, since usually an increase in density produces an increase in strength (Mellor, 1968). However, there are significant exceptions to this relationship; for example, depth hoar will be much weaker than sintered and well bonded snow of the same density.

Snow hardness is a more valuable indicator of instability because of its direct relation to snow strength; in most cases an increase in hardness results from an increase in the number and strength of intergranular bonds. It also provides a means of identifying potential sliding surfaces. Very hard layers, such as crusts or those composed of clustered grains, can provide cohesive and relatively frictionless upper surfaces and thus can significantly destabilize overlying snow layers.

4.2.5 Free water content

The free water content of a snowpack is an extremely useful index of instability, particularly in the spring. The depth of significant wetting represents the depth to which the destruction of grain bonds by melting has proceeded. This level therefore should be an approximate indicator of the potential magnitude of avalanching. Some degree of instability is almost certainly present when wet snow is underlain by an ice or crust layer or the ground. Free water also provides a positive feedback mechanism in the progress of a snowpack toward isothermal (and thus unstable) conditions: a rapid acceleration of melting occurs once the snow surface has become saturated, as a result of the low albedo of wet snow (approximately 60% compared to 90% or greater for dry snow [Armstrong, 1976]).

4.2.6 Mechanical tests

Mechanical testing provides low entropy information on the location and degree of snowpack weaknesses. While not providing the kind of conclusive evidence that can only be obtained by test skiing or using explosives on actual avalanche paths, the ram and shovel shear tests do supply the most useful information available from the study site.

4.2.6.1 ram test

The increment of penetration of a rammsonde per hammer blow increases substantially when it passes through a weak snow layer (Perla and Martinelli, 1976). These weak layers are then exhibited as conspicious dips in the calculated ram profile, providing a ready means of locating potential sources of snowpack instability. From 33 avalanche fracture line profiles obtained in the San Juan Mountains of Colorado (Armstrong and Ives, 1976), an average ram number of 42 Newtons was derived from dips which corresponded to failure planes.

The ram test is useful for providing an index of deep instability in a continental snowpack (LaChapelle, 1966). This is primarily the result of the fact that depth hoar provides minimal resistance to rammsonde penetration. The test is especially valuable for locating the top of the depth hoar layer, as the rammsonde almost always plunges to the bottom of the snowpack upon encountering it. This attribute of the rammsonde has been widely recognized (e.g. Judson, 1967), and was observed in several ram tests carried out in the course of this research (Appendix 2). Keeler and Weeks (1968) note that in distinquishing temperature gradient layers in snowpacks, the ability to discern the top of the depth hoar layer from the ram number is more the result of change in ram number for a given density than to basic differences in density between temperature gradient and equi-temperature snow.

4.2.6.2 shovel shear test

The shovel shear test, although subjective, provides the closest approximation to actual slab avalanche release. Hence, it yields the most dependable information on the locations and levels of snowpack instability.

The relation between the shovel shear test and naturally triggered avalanching was investigated by Stethem and Tweedy (1981) at Whistler Mountain (Coast Range) and Granite Mountain (Rossland), British Columbia. Their results indicate that failure planes in new and old snow located with "very easy" and "easy" shovel shear classifications (Appendix 1) are weak enough to produce natural avalanches. A similar association was found with "moderate" shears in older snow layers.

4.3 Snowpack Development and Instability, 1982-83

4.3.1 Snowpack development

Snowpack depths at the Fortress Mountain and Highwood Pass study sites displayed a peak in the middle of January (Figures 4.1 and 4.2 and Appendix 2), with a subsequent drop until nearly the end of February when snowpack depths increased again. The January peak was the product of a major snowfall event on 9-10 January (22 mm at Fortress Mountain and 67 mm at Highwood Pass water equivalent), after which a lack of new snow accompanied by settling of the existing snow at both study sites resulted in shallowing of the snowpack through February. Increased snowfall in March was reflected in greater snowpack depths, with peaks occurring in early April at both study sites. Despite major snowfalls after this time snowpack depths gradually decreased (Figures 4.1 and 4.2 and Appendix 2). At Highwood Pass a 1 May snowpack depth of 134 cm was relatively shallow in comparison to previous years (Figure 1.7). The exact time of disappearance of the entire snowcover at the study sites is not known, but the time-lapse record indicates virtually bare slopes at Highwood Pass at the end of May; the Mount Inflexible #3 path was bare by the middle of that month.

Snowpack depths during the winter of 1982-83 can be compared to data from Highwood Pass for the winters of 1980-81 and 1981-82 (Figure 4.3) as well as to a long term average (see Figure 1.6). The previous years display a more gradual increase in snowpack depths, implying that the January peak in depths in 1982-83 was the product of an unusually heavy snowfall event. However, snowpack depths in 1980-81 and 1981-82 also peaked during the month of April. Smith (1979) notes this April maximum snow depth to be characteristic in Kananaskis Country (Figure 1.6).

The development of snowpack structure over the winter of 1982-83 at both the Fortress Mountain and Highwood Pass study sites followed the general seasonal evolution of a snowpack in a cold subhumid continental climate.

Temperature gradient metamorphism, resulting in the production of weak depth hoar layers, predominated early in the season (Plate 4.3). Warmer temperatures and deeper snowpacks later in the winter caused a shift to equi-temperature metamorphism and the formation of well bonded and well rounded snow grains. Selected profiles from

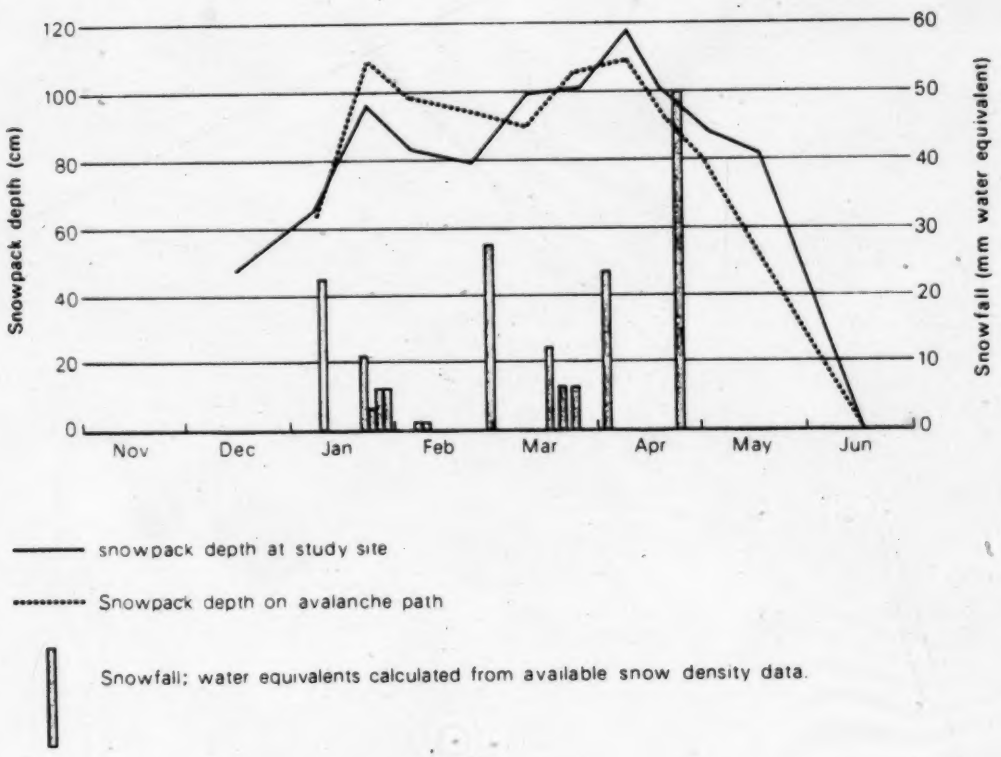


Figure 4.1 Summary of snowpack depths and snowfall; Fortress Mountain, 1982-83

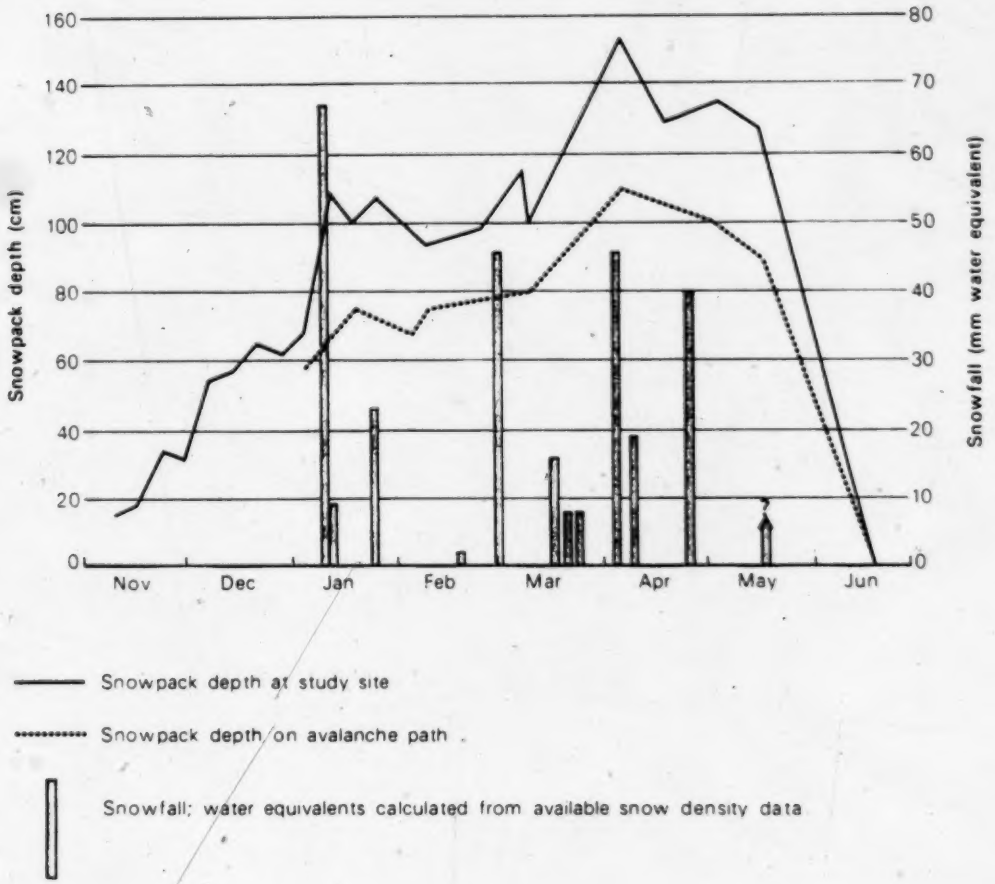


Figure 4.2 Summary of snowpack depths and snowfall; Highwood Pass, 1982-83

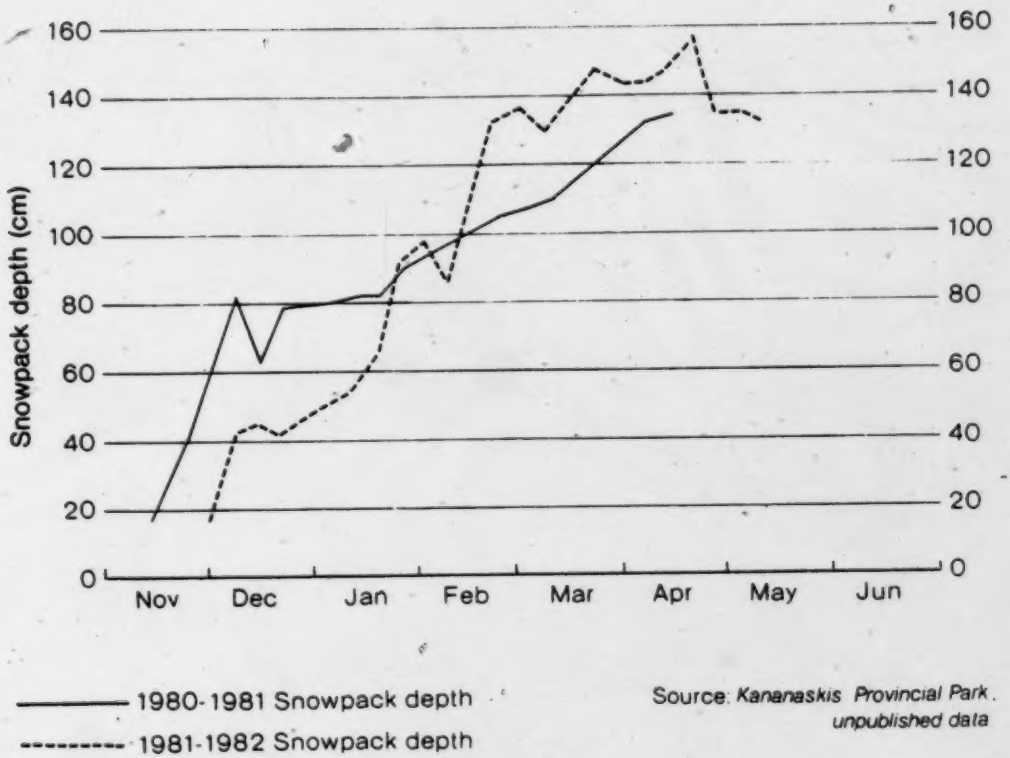


Figure 4.3 Snowpack depths at Highwood Pass, 1980-81, 1981-82.

Plate 4.3 5 February 1983 snow profile, Fortress Mountain study site. Basal depth hoar layers are clearly visible.

the two study sites (Figures 4.4 and 4.5) illustrate the prevalence of steep negative temperature gradients early in the winter, with shallower gradients and eventually isothermal conditions becoming dominant as the season proceeds. The progression, however, is clearly not a smooth one, especially in the upper layers of the snowpack where the effects of shorter term air temperature variations are felt.

Spring, with associated heavier snowfalls and the rise of air temperatures above freezing, produced a highly complex stratigraphy of new snow layers, grainy old snow and melt-freeze crusts (Plate 4.4). Basal layers of depth hoar grains produced early in the winter, however, persisted throughout the spring even though the grains were altered by equi-temperature metamorphism (Appendix 2 and Figures 4.6 and 4.7). Although the snowpacks at both study sites followed this general progression, specific temperature and precipitation characteristics over the winter modified it somewhat.

The presence of temperature gradient metamorphism is largely determined by air temperatures and snowpack depths in order to provide sufficiently steep temperature and vapour pressure gradients. Using Armstrong's (1981) straightforward calculation for an average long-term temperature gradient (mean monthly air temperature divided by mean monthly snow depth), the Fortress Mountain study site snowcover should theoretically have been under the influence of temperature gradient metamorphism in November, December and January. However, short term variations in air temperatures and snowpack depths render such monthly averages almost useless for determining the presence of temperature gradient metamorphism. For example, a rise in air temperatures midway through December (Figure 2.3) resulted in the development of only immature depth hoar grains (16 December; Appendix 2). At the beginning of January a drop in temperatures produced depth hoar grains in all layers of the snowpack. By the middle of the month increased temperatures and snowpack depths resulted in these grains being confined to the basal half of the snowcover. Thus, unless air temperature and snowpack depth variations are minimal during the month, Armstrong's calculation has severe limitations. Such average snowpack temperature gradients, moreover, do not take into account their non-uniform character through the snowcover.

Equi-temperature metamorphism became dominant in February even though snowpack depths decreased. By March a complex stratigraphy of well rounded and well

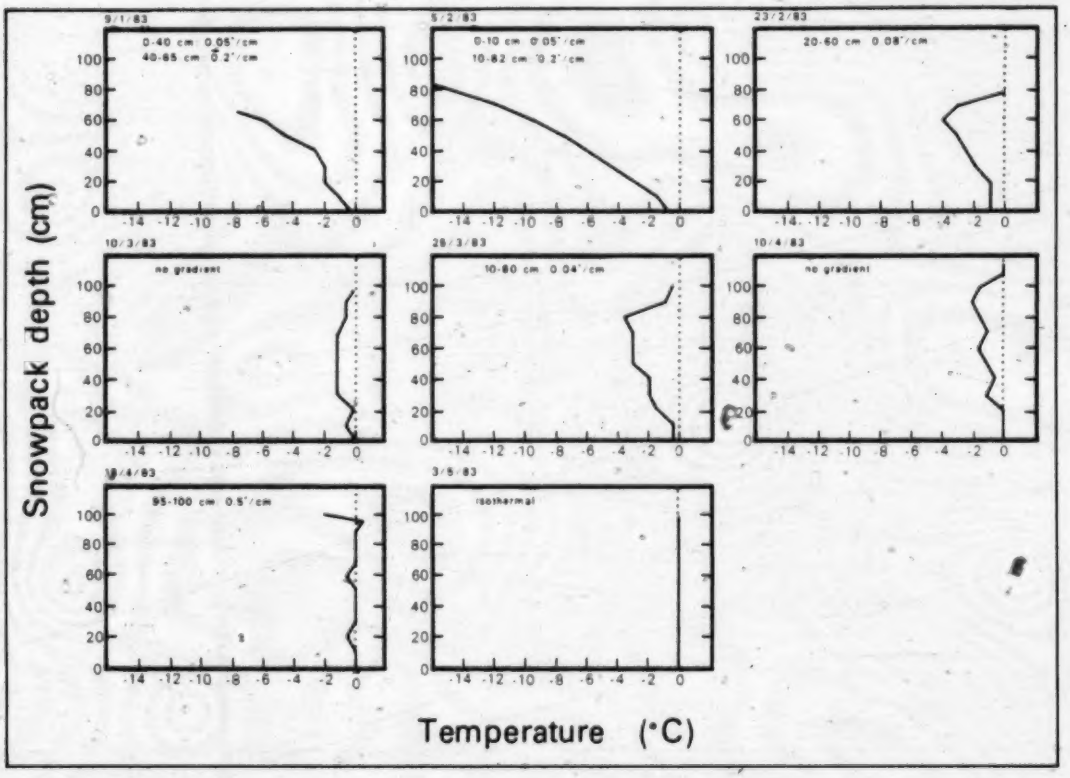


Figure 4.4 Selected snowpack temperature profiles; Fortress Mountain, 1982-83. Values indicate magnitude of negative temperature gradient.

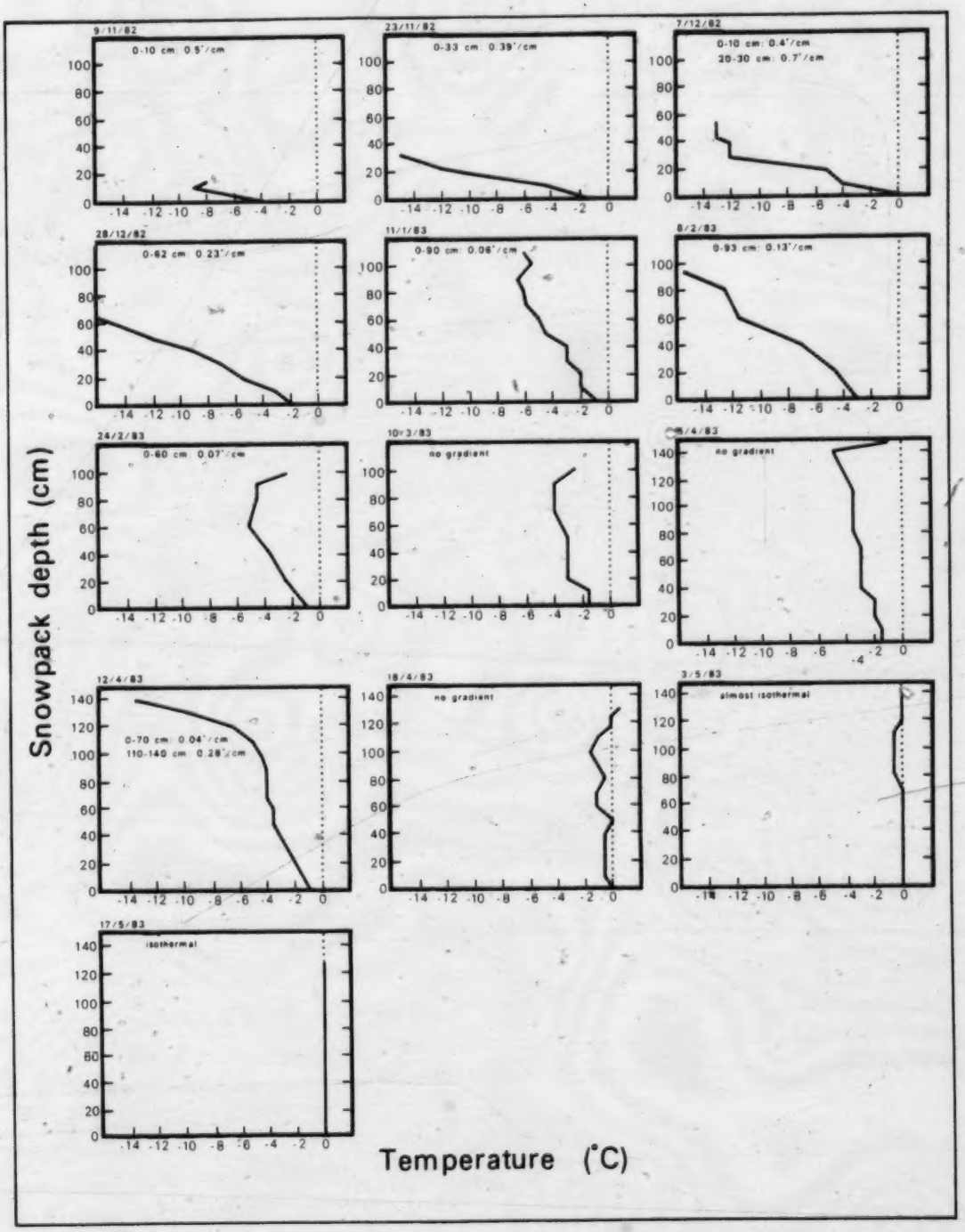
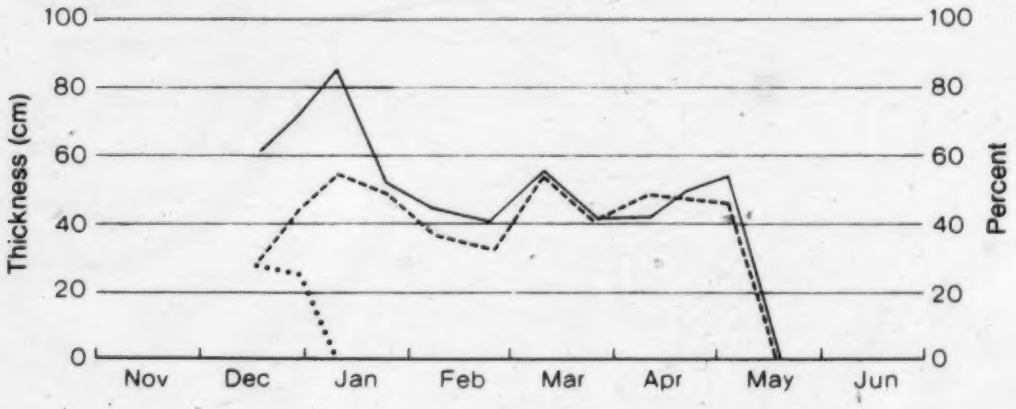


Figure 4.5 Selected snowpack temperature profiles; Highwood Pass, 1982-83. Values indicate magnitude of negative temperature gradient.

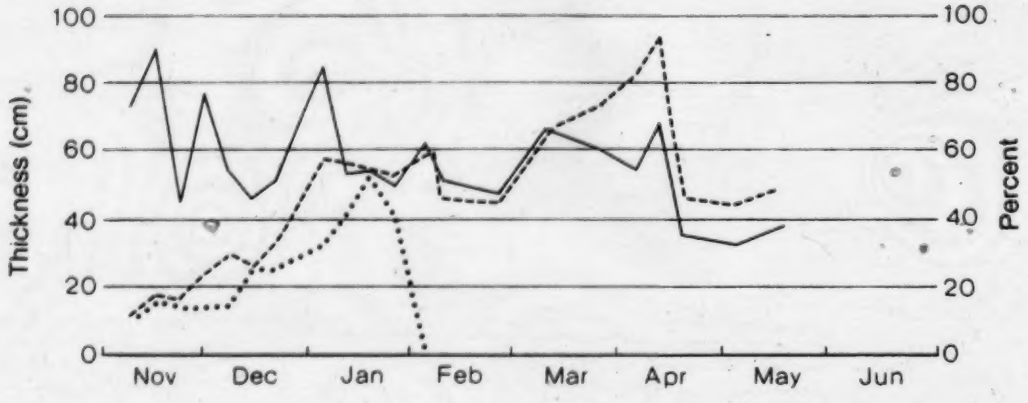


——— Thickness of depth hoar as a percentage of total snowpack

- - - - - - - Thickness (cm) of all depth hoar including layers altered by equitemperature metamorphism

····· Thickness (cm) of depth hoar unaffected by equitemperature metamorphism

Figure 4.6 Depth hoar in the snowpack; Fortress Mountain, 1982-83



——— Thickness of depth hoar as a percentage of total snowpack

- - - - - - - - Thickness (cm) of all depth hoar including layers altered by equitemperature metamorphism

..... Thickness (cm) of depth hoar unaffected by equitemperature metamorphism

Figure 4.7 Depth hoar in the snowpack; Highwood Pass, 1982-83

Plate 4.4 10 April 1983 snow profile, Fortress Mountain study site. Note the complex upper-snowpack stratigraphy; orange markers indicate layer interfaces. A hard ice layer is indicated by the white card.

bonded equi-temperature grains alternating with melt-freeze crusts had begun to develop as a result of daytime air temperatures well above 0°C (Figure 5.1). Coarse, granular melt-freeze grains did not develop until April, at which time the stratigraphy also provided numerous weak layer interfaces (Appendix 2). By May the snowpack structure had simplified, with the majority of the snowcover composed of hard, clustered melt-freeze grains, although the bottom layers still betrayed their temperature gradient genesis. The attainment of an isothermal condition in the entire snowpack coincided exactly with the time when mean daily air temperatures rose above 0°C.

Utilizing Armstrong's calculation, temperature gradient metamorphism should have dominated in the Highwood Pass snowpack in November and December. However, from snowpack observations it is evident that equi-temperature metamorphism was prevalent toward the end of December, when the rounding of angular depth hoar grains was noticed (Appendix 2). Colder air temperatures at the beginning of January resulted in a short resurgence of temperature gradient metamorphism, which ended with subsequent warmer temperatures and a deeper snowpack. After this equi-temperature metamorphism was clearly dominant, with the uppermost two-thirds of the snowpack composed of well rounded and well bonded grains. In March the first melt-freeze crusts appeared, which is surprising in light of the lack of above-freezing daytime air temperatures at this time (Figure 5.1). These were incorporated into the snowpack as new snow was deposited on top of them. Coarse, granular melt-freeze snow did not appear in significant quantities until May (17 May; Appendix 2), following warm daytime air temperatures in late April. The entire snowcover reached an isothermal condition at this time in May. Snow in the basal layers of the snowpack retained its depth hoar character throughout the entire spring.

Figures 4.6 and 4.7 summarize depth hoar in the snowpacks at Fortress Mountain and Highwood Pass. It is apparent that a vast majority of the snowcover was composed of some type of temperature gradient-metamorphosed snow until January. The persistence of depth hoar until the disappearance of the snowcover is also evident, even though it was rapidly altered by equi-temperature metamorphism.

Temperature gradient metamorphism is known to be dependent both on the temperature gradient and on the absolute temperature of the snowpack; they together determine the magnitude of the vapour pressure gradient, which in turn controls

temperature gradient metamorphism. To further elaborate on these relationships, an analysis was carried out to discover where exactly in the snow profiles of 1982-83 were vapour pressure gradients sufficiently steep for temperature gradient metamorphism; these were calculated on the basis of their relationship to temperature gradients and mean temperatures within the pore spaces of a snowcover (Armstrong, 1981). Figure 4.8 illustrates that such gradients had a tendency to migrate upward in the snowpack in the spring; this was produced by the replacement of long-term temperature gradients in the entire snowpack, as a result of persistent cold winter temperatures, by short-lived gradients in the upper layers only as a result of diurnal cycling of air temperatures. However, these 'spring' gradients did not produce any depth hoar grains, presumably because they were too short-lived, and possibly because the snow was too well settled to easily allow the movement of water vapour through it.

4.3.2 Snowpack instability

Utilizing the indices described earlier in this chapter, the level and source of snowpack instability was evaluated for each snow profile in Appendix 2 (Table 4.1). Avalanche hazard evaluation is inevitably a 'technical art' and relies on "numerical-intuitive" methods (Anderson *et al*, 1978). Thus the success of conventional avalanche hazard evaluation and forecasting is based on the intuitive and analytical skill of the avalanche worker, a skill which cannot be easily communicated by him (LaChapelle, 1966; 1970; 1980). LaChapelle (1974, p. 47) offers a simple but accurate parallel: "a master baker can judge unerringly the quality of bread dough, but he cannot explain in words how he does it". The levels of instability at the study sites were determined by a similar intuitive evaluation of all available data. However, it is felt that they represent a reasonably accurate picture of the pattern of instability through the winter (Figure 4.9).

Although no data are available for November, the level of snowpack instability at Fortress Mountain in this month was probably low because of insufficient snow. A moderate level of instability was present in mid-December, and continued until approximately mid-March, caused primarily by weak depth hoar underlying cohesive layers of newer snow (Plate 4.3 and Appendix 2). It is significant to note that although the production of depth hoar grains was inhibited by warmer temperatures in mid-December

Table 4.1 Snowpack instability, 1982-83

DATE OF SNOW PROFILE	AVALANCHES RECORDED (number and size)	SNOWPACK DEPTH* (cm)	LEVEL OF SNOWPACK INSTABILITY
Fortress Mountain ("Mt. Inflexible #3")			
16/12/82	one, size 2	47	MODERATE; moist snow layers on depth hoar
9/1/83	several, size 2-3	65	MODERATE; thick depth hoar layers
23/1/83	no	95	MODERATE; thick depth hoar layers
5/2/83	three, size 2	82	MODERATE; cohesive slab of equi-temperature snow on depth hoar
23/2/83	no	78	MODERATE; slab still not well bonded to depth hoar
10/3/83	one, size 3	98	MODERATE; wet snow comprising the upper layers
20/3/83	two, size 1-2	98 (117)	MODERATE; 2-3 cm graupel layer buried in upper part of snowpack
25/3/83	one, size 2-3	100	HIGH; ice and crust layer providing poor cohesion in upper part of snowpack
10/4/83	one, size 3	117	HIGH; poor cohesion between melt-freeze and equi-temperature snow layers in upper part of snowpack
18/4/83	twelve, size 2-4	100	HIGH; 25 cm of wet snow overlying moist snow. Surface crust very poorly bonded to underlying layers
3/5/83	approx. twelve, size 2-4	87 (102)	HIGH; snowpack isothermal. Weak layer interfaces between melt-freeze and equi-temperature snow
18/5/83	one, size 2	>80	VERY HIGH; Snowpack isothermal. Extremely weak, moist melt-freeze snow
Highwood Pass			
9/11/82	no avalanche record	15	LOW; insufficient snow
16/11/82		18	LOW; insufficient snow
23/11/82		33	LOW; insufficient snow
30/11/82		31	LOW; insufficient snow
7/12/82		54	MODERATE; weak depth hoar
14/12/82		57	MODERATE; weak depth hoar and crusts in the upper layers
21/12/82		65	MODERATE; thick depth hoar layers
28/12/82		62	MODERATE; thick depth hoar layers
4/1/83		67	MODERATE; thick depth hoar layers
11/1/83	several, size 2-3	108 (130)	MODERATE; thick depth hoar layers
18/1/83	no	100	HIGH; weak basal depth hoar
25/1/83	two, size 2 & 3	107	LOW; depth hoar under influence of equi-temperature metamorphism
3/2/83	no	98	LOW; depth hoar under influence of equi-temperature metamorphism
8/2/83	no	93	LOW; depth hoar under influence of equi-temperature metamorphism
24/2/83	no	98	LOW; depth hoar under influence of equi-temperature metamorphism
10/3/83	one, size 2	99	LOW; depth hoar under influence of equi-temperature metamorphism
25/3/83	several, size 1-2	123	MODERATE; some crusts and incohesive new snow in upper part of snowpack
5/4/83	several, size 1-4	153	VERY HIGH; crust layer providing very poor cohesion to overlying newer snow layers
12/4/83	no	140	MODERATE; some melt-freeze snow and crusts providing weak layer interfaces in upper part of snowpack
18/4/83	one, size 2	129	VERY HIGH; numerous crust and ice layers in upper part of snowpack. Extremely weak old basal depth hoar
3/5/83	six, size 2-4	135 (156)	MODERATE; some ice layers in upper half of snowpack. Weak old depth hoar
17/5/83	approx. fourteen, size 1-2	127	HIGH; snowpack isothermal. Wet snow in upper layers as well as a weak crust-old snow interface

* Numbers in brackets indicate calculated snowpack depths immediately after a storm.

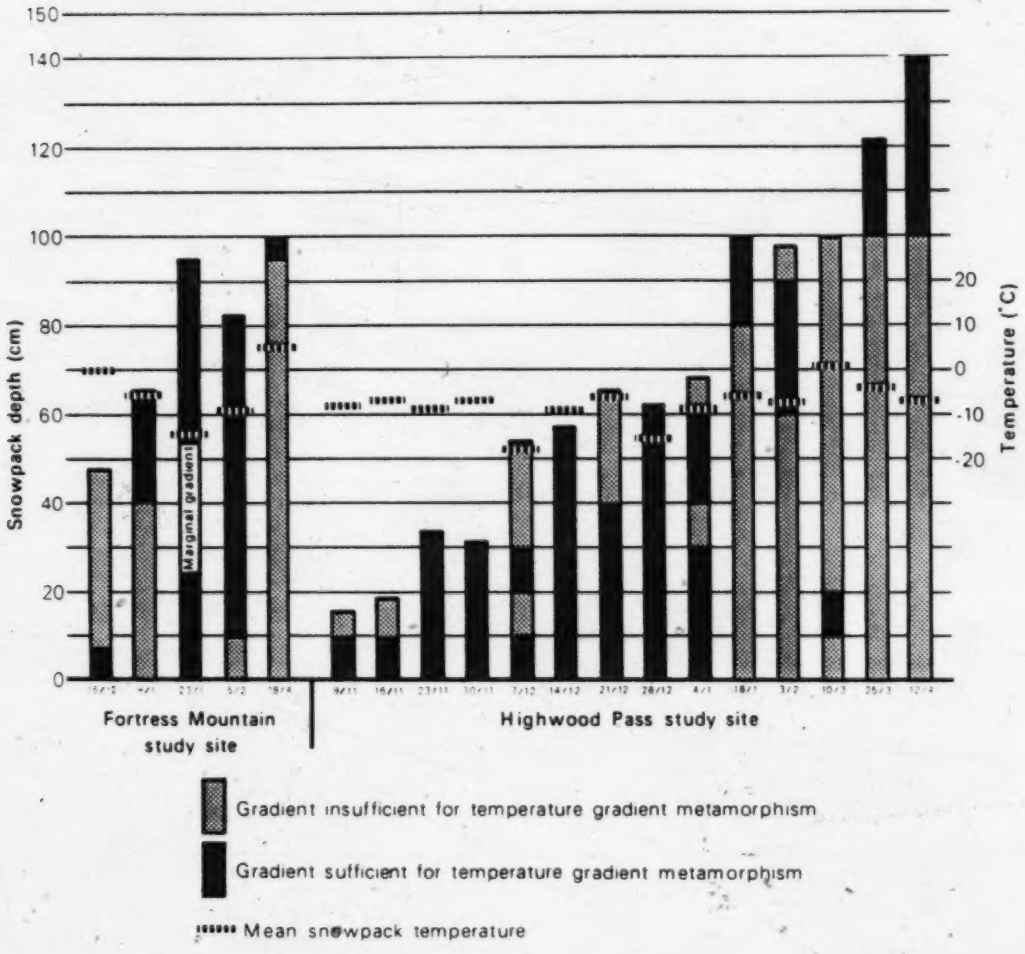


Figure 4.8 Vapour pressure gradients in the 1982-83 snow profiles. Based on a lower VPG of 5.0 mbar/m for low density snow (Armstrong, 1981).

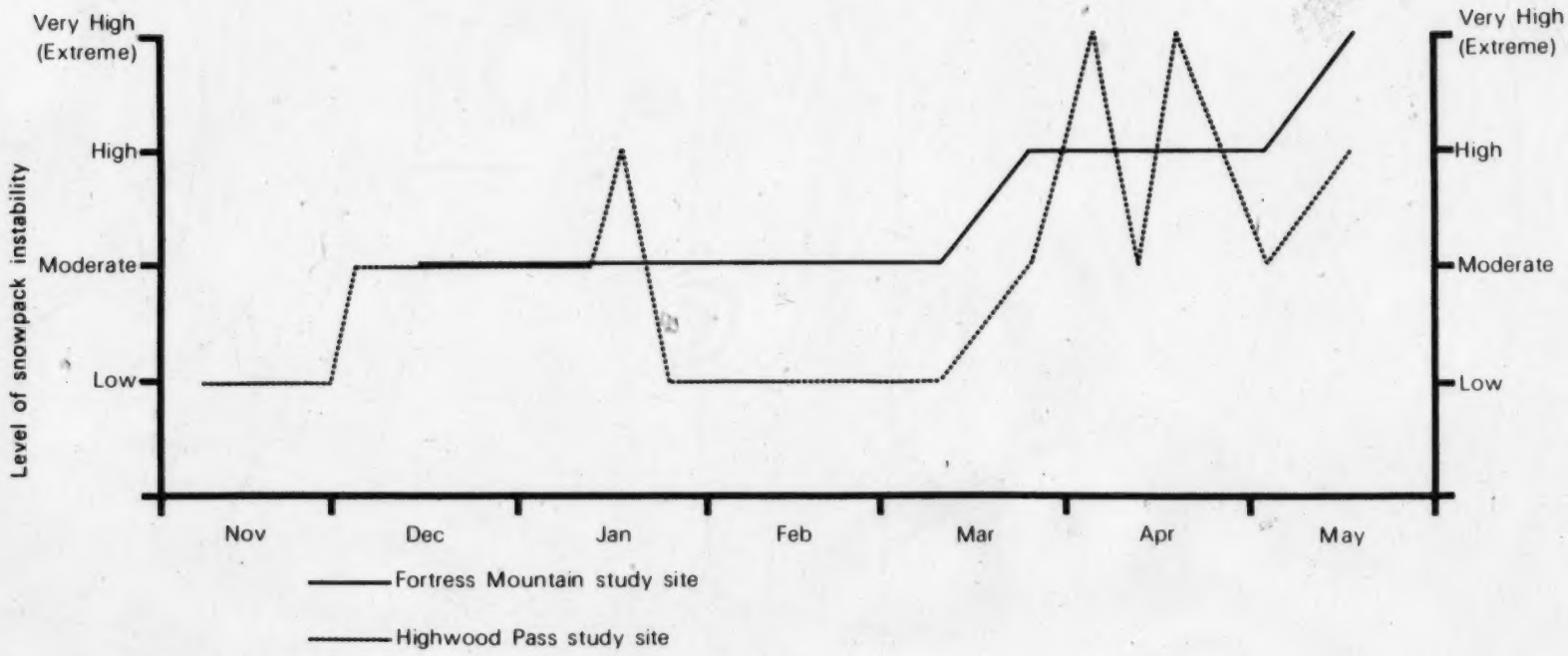


Figure 4.9 Snowpack instability, 1982-83

and probably did not take place after mid-January, they continued to destabilize the snowpack at least until the end of February. This instability was reflected in a number of "moderate" (Appendix 1) shovel shears deep in the snowcover. The moderate level of instability in March was caused first by layers of wet snow in the upper part of the snowpack, and later by the presence of a buried layer of cohesionless graupel.

Snowpack instability from the end of March until early May was evaluated as high, reflecting the development of the increasingly complex stratigraphy of melt-freeze grains, crusts and newer, fine-grained snow in the upper layers of the pack (Plate 4.4 and Appendix 2). The presence of a number of weak layer interfaces in this region was revealed by "easy" (Appendix 1) and distinct, planar shovel shears. Increasing amounts of free water in the snowpack, as it neared isothermal conditions, contributed to the high level of instability. By 3 May the entire pack was isothermal and composed of wet snow. The 18 May snow profile (Appendix 2) was evaluated as being extremely unstable. The structure had by this time simplified, and the snowpack was composed almost entirely of wet melt-freeze grains, bonded together only by surface tension.

At Highwood Pass the pattern of instability in 1982-83 was more complex (Figure 4.9). Temperature gradient metamorphism was dominant in most of the snowpack in November. However, instability levels were low during the entire month due to insufficient snow depths.

Despite the effects of equi-temperature metamorphism in late December, depth hoar, combined with increased snow depths, produced moderate instability from the beginning of December until approximately mid-January. This was reflected in a number of "moderate" and "hard" (Appendix 1) shovel shears in the lower half of the snowcover (Appendix 2). The resurgence of temperature gradient metamorphism in early January thickened and weakened the basal depth hoar: as a result, on 18 January the snowpack was evaluated as highly unstable, with an "easy" shovel shear being produced near the base of the pack (Appendix 2).

From the latter part of January until approximately mid-March, instability levels were low as depth hoar began to be influenced again by equi-temperature metamorphism and gained some strength.

The development of the first melt-freeze crusts and their subsequent burial by new snow in late March produced a moderate level of instability. At the beginning of April the snowpack had become extremely unstable, as a significant thickness of partially settled snow was very poorly bonded to an underlying melt-freeze crust (5 April; Appendix 2). This instability dropped briefly but appreciably in mid-April as layer interfaces gained some strength. However, the 18 April snow profile was evaluated as being extremely unstable again, due to numerous crusts and extremely weak, altered basal depth hoar (Appendix 2).

At the beginning of May instability had dropped to a moderate level; although a number of ice layers were present in the upper half of the snowpack, no "easy" shovel shears could be produced. Accompanying the attainment of isothermal conditions in the middle of the month, however, the snowpack again became highly unstable as a result of poorly anchored wet snow in the upper layers (Appendix 2).

4.4 Snowpack Instability and Avalanches

Table 4.1 compares snowpack instability and avalanche activity in 1982-83. It shows that high levels of instability did not always produce avalanches, and conversely avalanching was possible during periods of relatively low instability. For example, despite a high level of instability in the snow profile obtained on 18 January at Highwood Pass, no avalanches occurred around this date. Also at Highwood Pass, the 25 January and 10 March profiles were evaluated as having had low levels of instability; nevertheless, two avalanches of size 2 and 3, and one of size 2 were associated with these profiles respectively. Table 4.1 also shows that during some periods of moderate instability avalanching occurred, whereas with others none took place. Such inconsistencies in pattern may be the result of errors in the assessment of snowpack instability, considering the imprecise nature of this endeavour. However, they may also reflect the fact that whereas snowpack development can result in internal structural instability, such latent hazard requires an external triggering force of some type to produce actual failures. Without this triggering mechanism, unstable snow remains just that. LaChapelle's (1970) opinion that the triggering of latent instability, even in continental climates, is conditional on weather events was discussed in the literature review. From long term research in the San Juan Mountains of Colorado, Armstrong and Ives (1976) note that there also the setting of

unstable layers of snow into motion requires an external trigger. Mechanisms which triggered avalanches in the study areas in 1982-83 are treated in Chapter 5.

Concentrating on only avalanche triggers however is also unsatisfactory. From Table 4.1 it is obvious that the source of failure for many triggered avalanches in 1982-83 could have been in old snow layers, providing of course that the source of any instability had been correctly pinpointed. Thus the strength (or weakness) of these layers and layer interfaces is critical in determining the intensity of trigger required. LaChapelle and Armstrong (1976, p. 29) note:

> "This condition may vary from relatively large amounts of new snow falling on a stable substructure without causing failure, to light snowfalls causing a significant avalanche cycle due to the predominantly low mechanical strength and poor layer bonding of the old snow."

In the next section, the characteristics of actual avalanche failure planes, and of the snowpacks in which they were located, are examined. These provide insights into the types of snowpack weaknesses that were unstable enough to result in avalanches in 1982-83.

4.5 Avalanche Failure Planes and Associated Snowpack Characteristics, 1982-83

The individual snow profiles in Appendix 2 were used to locate the specific failure planes that released avalanches, and also to examine some characteristics of the snowpacks in which these failure planes occurred. The starting zones of the monitored avalanche paths were not accessible for examining snowpack conditions at the point of avalanche initiation; however, it is felt that the study site profiles provide reasonably analogous characteristics, even though a dose of intuitive judgement was necessary to locate some failure planes. Unfortunately, the failure plane of every recorded avalanche could not be located at the study sites, particularly for those that occurred earlier in the winter. Moreover, because the time-lapse monitoring systems only operated from the beginning of January on, there is no available record for December, when snowpack depths were already sufficient for avalanching. This bias in failure planes toward spring conditions (when the failures were also better reflected in the study site snowpack) is somewhat minimized by the fact that the vast majority of avalanches occurred at this time

(March-May. See Table 3.1). Even though such well-defined failure planes would be expected to produce slab avalanches, some fracture line profiles (10 March at Fortress Mountain; 10 March and 17 May at Highwood Pass) produced wet, loose snow releases.

The characteristics of the failure planes are presented graphically as 'fracture line' profiles in Appendix 3. Table 4.2 summarizes these characteristics.

4.5.1 Snowpack depth

Snowpack depths during the recorded avalanche events were examined in order to provide information on the depth of snow required for avalanching in 1982-83.

At the Fortress Mountain study site, the snowpack depth was 47 cm at the time of the first recorded avalanche (16 December). The time-lapse camera system was not operating yet at this time; however, a close inspection of the avalanche path (Mount Inflexible #3) indicated this to be the first release (larger than sluff size) of the winter.

At Highwood Pass, the lowest snowpack depth recorded during avalanching was 99 cm (10 March; see Table 4.2). However, this figure probably does not represent the minimum value, since there is no avalanche record until 8 January. Actual snow depths on the Highwood Pass avalanche slope averaged 24% lower than at the study site (Figure 4.2), as a result of cross-slope winds which removed snow in the vicinity of the measuring stakes. Depressions on the slope from which all the recorded avalanches originated (Figure 1.11), however, were estimated to have snow depths two to three times greater than at the study site.

4.5.2 Snow characteristics

The temperature of the entire snowpack during avalanche events was examined because, as noted earlier in this chapter, study site snowpack temperatures between -2.0°C and 0°C have been observed in the San Juan Mountains of Colorado to correspond to a greatly increased probability of wet snow avalanches (Armstrong, 1976). In nine out of twelve fracture line profiles in Appendix 3 which produced wet snow avalanches (10 and 20 March, 10 and 18 April and 3 and 18 May at Fortress Mountain; 18 April and 3 and 17 May at Highwood Pass), the entire snowpack had a temperature between -2.0°C and 0°C. The three profiles in which portions of the snowcover were below -2.0°C (25 March

Table 4.2 Avalanche failure planes, 1982-83

ID DATE OF AVALANCHE (1)	SIZE OF AVALANCHE (1)	DATE OF SNOW PROFILE	SNOWPACK DEPTH[1](cm)	SNOW TEMPERATURE at failure plane (°C)	GRAIN TYPE[2] above failure plane	GRAIN TYPE[2] at bed surface	SNOW DENSITY (SPEC. GRAV.) above failure plane	SNOW DENSITY (SPEC. GRAV.) at bed surface	SNOW HARDNESS above failure plane	SNOW HARDNESS at bed surface	FREE WATER CONTENT above failure plane	FREE WATER CONTENT at bed surface	RAM INDEX at failure plane (Newtons)	SHOVEL SHEAR INDEX at failure plane
Mount Inflexible #3														
27/1/83	3	5/2/83	62	-5.5	late ET	late TG - early ET	.29	.25	med. hard-hard	very soft	dry	dry	no data	moderate
9/3/83	3	10/3/83	66	-1.0	late ET	late ET	.19	.19	med. hard	med. hard	wet	dry	22	none
20-21/3, 22/3/83	1-2	20/3/83 (reconstruction of 10/3/83)	98 (117)	0.0	graupel	clustered late ET	.21	.27	no data	hard	no data	no data	10	no data
24/3/83	2-3	25/3/83	100	-3.0	clustered late ET	ice	no data	no data	hard	ice	dry	dry	76	none
6/4/83	3	10/4/83	197	-1.5	clustered MF grains	late ET	no data	35	hard	med. hard	dry	dry	76	easy
30/4, 19/4, 20/4, 21/4/83	2-4	18/4/83	100	0.0	clustered late ET/crust	late ET	no data	30	hard	med. hard-hard	wet	moist	22	hard
24-25/4, 29/4-3/5, 4/5, 5/5, 8/5/83	2-4	3/5/83	87 (102)	0.0	clustered MF grains	late ET	41	no data	med. hard	hard	wet	wet	38	easy
11/5/83	2	10/5/83	80	0.0	clustered MF grains	clustered MF grains	no data	no data	med. hard	med. hard-hard	moist	moist	24	very easy
Highwood Pass														
9-10/1/83	2-3	11/1/83	100 (130)	-5.5	early ET - late ET	late ET	30	22	med. hard	med. hard	dry	dry	no data	none
3/3/83	1-2	10/3/83	66	-4.0	late ET - MF grains	early TG - clustered late ET	24	18	med. hard	med. hard	dry	dry	25	hard
3-4/4, 5/4, 6/4/83	1-4 (including Highwood Pass #5)	5/4/83	153	-3.5	early ET	MF crust	17	no data	soft-med. hard	med. hard	dry	moist	no data	very easy
27/4/83	2	30/4/83	126	-1.5	clustered MF grains/crust	late ET	no data	33	hard	hard	moist	moist	23	easy-moderate
24-25/4, 6/5/83	2-4 (including Highwood Pass #2)	3/5/83	136 (156)	-0.5	early ET	ice	25	no data	med. hard	ice	moist	moist	28	none
15/5, 22/5, 23/5/83	1-2	22/5/83	127	0.0	crust/ice	late ET - MF grains	no data	41	crust/ice	hard	wet	moist	27	easy

[1] Numbers in brackets indicate calculated snowpack depths immediately after a storm

[2] ET - equi-temperature (metamorphism)
TG - temperature gradient (metamorphism)
MF - melt-freeze (metamorphism)

at Fortress Mountain; 10 March and 5 April at Highwood Pass) represented situations where recently deposited snow had become unstable through subsequent warming. These point out the danger of relying on Armstrong's -2.0°C threshold for other than evaluating late-spring instability. Unconsolidated new snow can be warmed to instability even if deposited on top of a snowpack still in a midwinter temperature regime.

The bed surface temperatures of the failure planes in Appendix 3 were examined (Table 4.2). These compare well with the range of temperatures measured by Perla (1977) and Stethem and Perla (1980); from -5.5°C to 0°C, with a mean of -1.8°C. Although the reason why temperatures in this range cause snowpack instability is not known, there does appear to be an association between the two.

Snow above and below the failure planes in Appendix 3 was analyzed for its density, hardness and moisture content.

The relatively high specific gravities (on average .29, or 290 kg m^{-3} density) and hardnesses of snow comprising the bed surfaces (Table 4.2) indicate that reasonably hard and cohesive layers were required for sliding surfaces. This is reinforced by the presence of three ice and crust layers which acted as bed surfaces, and which had very high densities and hardnesses. In only one instance was very soft snow (in this case depth hoar grains) found below a failure plane. Its lack of cohesion implies that it did not provide a smooth bed surface but rather collapsed on failure. In fact, its density (230 kg m^{-3}) is comparable to Stethem and Perla's (1980) average lubricating layer ("Gleitschicht".See Figure 1.1) density of 200 kg m^{-3}.

Snow above the failure planes also exhibited high specific gravities (mean of .26, or 260 kg m^{-3}) and hardnesses (Table 4.2), indicating that failures were caused by a lack of cohesion between two relatively dense and hard layers.

As is illustrated in Table 4.2, free water in the snow and the associated destruction of intergranular bonding became increasingly more common at failure planes in the spring. Increased water content was closely linked to the approach of isothermal snowpack conditions; seven out of the eight failure planes with moist or wet snow either above or below them had a temperature between -1.5°C and 0°C.

Three fracture line profiles in Appendix 3 exhibit a marked change in free water content of snow at the failure plane (Table 4.2). The wetter snow above the failure

reflects heating of the snowpack from the surface downward, and also that portion of the snowpack where intergranular bonding has been destroyed. This is clearly illustrated by the 9 March avalanche on the Mount Inflexible #3 path, where the location of the failure plane was determined solely from the depth of wetted snow.

4.5.3 Grain types

Depth hoar provided a source of snowpack instability at both study sites in early winter and midwinter (Table 4.1), but only one avalanche failure plane in Appendix 3 possessed this grain type, in this instance at the bed surface (Table 4.2). The role of depth hoar grains in snowpack failure in 1982-83 is unknown for two reasons: no avalanche record is available for December at Highwood Pass, and the failure planes of avalanches were generally difficult to locate in January and February even when a record was available.

Since the spring produced the largest number of avalanches in 1982-83 (Table 3.1), most bed surfaces were characterized by well rounded grains in advanced stages of equi-temperature metamorphism, and melt-freeze snow ranging from clustered grains to crust (Table 4.2). In two instances an ice layer provided a hard and cohesive bed surface.

The fracture line profile for the 3-6 April avalanches at Highwood Pass (Appendix 3) illustrates the typical formation of a spring-time crust bed surface. A number of days of clear skies and somewhat warmer temperatures preceding the 3-4 April snowfall (Figures 2.3 and 5.1) resulted in the formation of a melt-freeze crust on the snowpack surface. This provided a very poor anchor for the new snow soft slab formed on 3-4 April and the subsequent wet snow on 5 and 6 April. This type of development is primarily a spring phenomenon, but can occur at any time when warmer weather precedes a drop in air temperatures and snowfall. Latent instability will continue to exist at the crust surface even though the first snowfall may not avalanche on it. However, once these crusts become deeply buried they usually cease to be a problem (Perla and Martinelli, 1976).

Snow above the failure planes was for the most part composed of advanced equi-temperature and melt-freeze grains. On three occasions a thick and cohesive crust was incorporated into the slab itself and slid on a bed surface to which it was poorly

bonded. This seems to indicate that instability does not have to be confined to the *top* surface of a crust or ice layer.

In two profiles the snow above the failure plane was composed of partially settled new snow (early equi-temperature. See Table 4.2). The failure in both cases occurred at the old-new snow interface rather than within the old snow structure, as a result of poor bonding of the new snow to a surface crust. A similar failure produced the avalanches of 24-25 April on the Mount Inflexible #3 path (Appendix 3), except the snowpack surface (i.e. bed surface) consisted of advanced equi-temperature grains, and the new snow above the failure plane had metamorphosed into clustered melt-freeze grains by the time the profile was obtained at the study site.

Lubricating layers ("Gleitschichten") were not numerous among the fracture line profiles in Appendix 3, being present at only two failure planes. Between 20 and 22 March on the Mount Inflexible #3 path 2 cm of buried graupel provided a lubricating layer for several avalanches. The second one consisted of advanced equi-temperature grains, and assisted in releasing an avalanche at Highwood Pass on 17 April. The lack of others implies that a thick and distinct lubricating layer of snow weak in shear is not necessary to cause failure, as long as the slab is poorly bonded to the slab substratum. A similar observation has been made about failure planes in the San Juan Mountains of Colorado (Armstrong *et al*, 1974: LaChapelle and Armstrong, 1976). Stethem and Perla (1980) note that even when present, the lubricating layer rarely exceeds 50 mm in thickness.

4.5.4 Mechanical tests

Ram (rammsonde) profiles were obtained for eleven of the fourteen fracture line profiles in Appendix 3. A rammsonde was unavailable for the other three profiles.

All eleven ram profiles exhibit a conspicious dip or low value at the failure plane. Ram numbers at this location range from 10 (the lowest the standard rammsonde can record) to 38 Newtons, with a mean of 25. This trait of the ram profile , while it did not point to the causes of snowpack failure, reinforced the identification of the failure plane location.

The shovel shear test produced "very easy" and "easy" (Appendix 1) shears at six of the failure planes in Appendix 3. It provided the most unequivocal study site evidence of

avalanche failure plane locations. These "very easy" and "easy" shovel shears were not associated with failure planes until April, appearing contemporaneously with the complex stratigraphies of advanced equi-temperature and melt-freeze snow, and crusts. Prior to this only "moderate" and "hard" (Appendix 1) shovel shears had been associated with any failure plane.

Four failure planes were not associated with any shovel shear (Appendix 3 and Table 4.2), while two were associated with "hard" shears. This seems to indicate that significant snowpack instability may not be picked up by an "easy" or "moderate" shovel shear, or in fact by any shear.

4.6 Summary

Snow profile data were used to assess the pattern of snowpack development and instability during the winter of 1982-83 at the Fortress Mountain and Highwood Pass study sites. Because snowpack instability does not necessarily cause avalanches, and the locations of snowpack failures may differ from the expected sources of instability, the data were also used to locate the failure planes of avalanches recorded by the time-lapse monitoring systems. These data were collected utilizing well established indices of snowpack stability. Among these, the ram and shovel shear tests and the snow hardness index were the most useful.

The development of snowpack structure at both study sites was characteristic of a snowcover in a cold subhumid continental climate, with short-term temperature and precipitation trends accounting for variations from the general pattern. Relatively warm air temperatures in mid-to late December inhibited the growth of depth hoar in the shallow early winter snowpack at both study sites. Colder weather at the beginning of January however resulted in a resurgence of temperature gradient metamorphism. Equi-temperature metamorphism once again became dominant in the middle of the month when increased snowpack depths, as a result of an unusually heavy snowfall, were accompanied by warmer weather.

During the month of February, equi-temperature metamorphism continued to dominate at both study sites despite shallowing of the snowpacks as a result of settling and lack of snowfall. The absence of temperature gradient metamorphism can most likely

be attributed to slightly higher air temperatures in this month.

From March to May at both study sites the upper snowpack stratigraphy of melt-freeze grains, crusts and equi-temperature snow became increasingly complex, providing numerous weak layer interfaces. Characteristically, the cohesive strength of melt-freeze grains near the top of the snowpack was greatly dependent on whether air temperatures were above or below freezing. Depth hoar at the base of the snowpack became increasingly rounded in spring, but remained relatively incohesive and very weak; a trait of depth hoar which has been noted by several authors (e.g. LaChapelle and Armstrong, 1976).

The pattern and sources of instability over the winter closely reflected the development of the snowpack at both study sites.

Despite the dominance of temperature gradient metamorphism in November, the snowpacks at both study sites remained stable due to shallow snow depths. At Fortress Mountain the snowpack became moderately unstable in mid-December and remained so until mid-March. Depth hoar deep in the snowpack was at first responsible, even though its development had been hindered in mid-December. Later on the cause of the moderate instability shifted to wet snow and then a buried layer of graupel, higher in the snowpack. At Highwood Pass, the level of instability became moderate from the beginning of December until mid-January. The cause was again weak depth hoar, despite the dominance of equi-temperature metamorphism in late December.

From late January until mid-March, instability at Highwood Pass dropped to a low level, as depth hoar production was replaced by equi-temperature metamorphism and the snowpack gained some strength.

At the end of March instability levels at Fortress Mountain rose to a high level, coinciding with the development of the increasingly complex stratigraphy of melt-freeze snow, crusts and equi-temperature snow. This instability persisted all spring, and rose to a very high level in May when the snowpack reached an isothermal condition and lost much of its cohesive strength.

At Highwood Pass a similar jump in instability levels occurred in late March, again coinciding with an increasingly complex upper snowpack stratigraphy. However, instability until late April varied from moderate to very high. Altered but extremely weak,

basal depth hoar contributed to the unstable condition of the snowpack. In early May instability levels had dropped to moderate, as layer interfaces gained some strength. By the middle of the month however they had once again risen to a high level, as the snowpack reached an isothermal condition and poorly anchored wet snow comprised the top layers.

Shovel shear test results in 1982-83 reflected the pattern of instability at both study sites. Early in the winter, with depth hoar a dominant source of instability, a number of "moderate" and "hard" (Appendix 1) non-planar shears were produced deep in the snowpack. In the spring however numerous "easy" and some "very easy" planar shears higher in the snowpack reflected the increasing role of weak layer interfaces in causing instability.

The examination of failure planes in avalanche fracture line profiles provided an insight into the characteristics of actual failures, and of the snowpacks in which these occurred. The fracture line profiles indicate that much less than one metre of snow was necessary on the avalanche paths to produce relatively large avalanches (size 2 to 3). This is due to the lack of anchoring mechanisms, such as brush, in the starting zones and upper track sections of both paths.

Wet snow avalanches were associated with temperatures in the entire study site snowpack between -2.0°C and 0°C, except where new snow deposited on top of a 'cold' snowcover had been heated by the sun. A change in moisture content at the failure plane was characteristic of some wet snow avalanches.

Temperatures at failure planes were found to lie within a narrow range; between -5.5°C and 0°C, although the reason for this is unknown.

Grain types both above and below the failure planes were composed primarily of well rounded, advanced equi-temperature or melt-freeze grains, crust or ice. Most exhibited relatively high densities and hardnesses, except in one situation where very soft depth hoar comprised the bed surface. Some partially settled new snow was also present above failure planes, representing situations where the failure occurred at the old-new snow interface rather than within the old snow structure.

Lubricating layers could be identified at only two failure planes, supporting the opinion of other authors that they are not essential for producing snowpack failure and

avalanching (Armstrong *et al*, 1974; LaChapelle and Armstrong, 1976).

The mechanical tests employed were found to be very useful for identifying failure planes. Ram profiles consistently exhibited low numerical values at the failures. The shovel shear test provided the best evidence for failure plane locations because it directly, even if subjectively, indicated the shear strengths of the snowpack layers and layer interfaces. However, the test in some cases missed failure planes that were present, which seems to indicate that it is not a foolproof technique for evaluating snowpack instability.

5. AVALANCHE TRIGGER MECHANISMS, 1982-83

The requirement for some type of mechanism to trigger an unstable snowpack into motion was discussed in the literature review and briefly in Chapter 4. The possible types of triggers were also outlined. Artificial mechanisms can be discounted as having been triggers for any of the recorded 1982-83 avalanches, since both monitored paths were relatively inaccessible - Mount Inflexible #3 because of its size and thick brush in the lower reaches, and Highwood Pass because of its remoteness. Likewise, several of the natural triggering mechanisms outlined can either be discounted as implausible or being incapable of producing the frequency and magnitude of avalanching that occurred in 1982-83. Short-term weather events were the most likely triggers for the recorded avalanches, because every avalanche event was closely associated with snowfall or a rise in air temperatures to above 0°C (thawing) (Figure 5.1). Moreover, the importance of weather as a trigger of avalanche activity has been widely recognized in the avalanche literature (e.g. LaChapelle, 1970; Perla and Martinelli, 1976). No spontaneous ('climax') avalanches were triggered in 1982-83 by gradual adverse metamorphism of the snowpack. Only one (loose snow) avalanche (28 March at Highwood Pass [Table 3.1]) was not directly related to a weather event, although it was most likely a delayed action release from the previous week's snowfall. Thaw triggering may also have been a factor, since study site air temperatures were relatively high (-7.0°) and the slope was in direct sunlight prior to the release.

Highwood Pass, with generally colder air temperatures and heavier snowfalls (Figures 2.3, 4.1 and 4.2), experienced a larger number of snowfall triggered avalanches than the Mount Inflexible #3 path, where thaw triggered releases were more common. The exception at Highwood Pass occurred in May, when a large number of thaw triggered releases were recorded.

By comparing the weather record with the avalanche record for 1982-83, the relative importance of each trigger can be quantified. Table 5.1 shows that snowfall triggered 20% of all avalanches on the Mount Inflexible #3 path and 31% at Highwood Pass. Rises in air temperature triggered 55% and 44% of avalanches on Mount Inflexible #3 and at Highwood Pass respectively (the relatively high value at Highwood Pass reflects the great increase in thaw triggering in May). A significant number of avalanches- 25% of

Table 5.1 Relative importance of avalanche trigger mechanisms, 1982-83

	Snowfall %	Rise in air temperature %	Snowfall followed by rise in air temperature %
Mount Inflexible #3 avalanche path	20	55	25
Highwood Pass avalanche slope	31	44	25

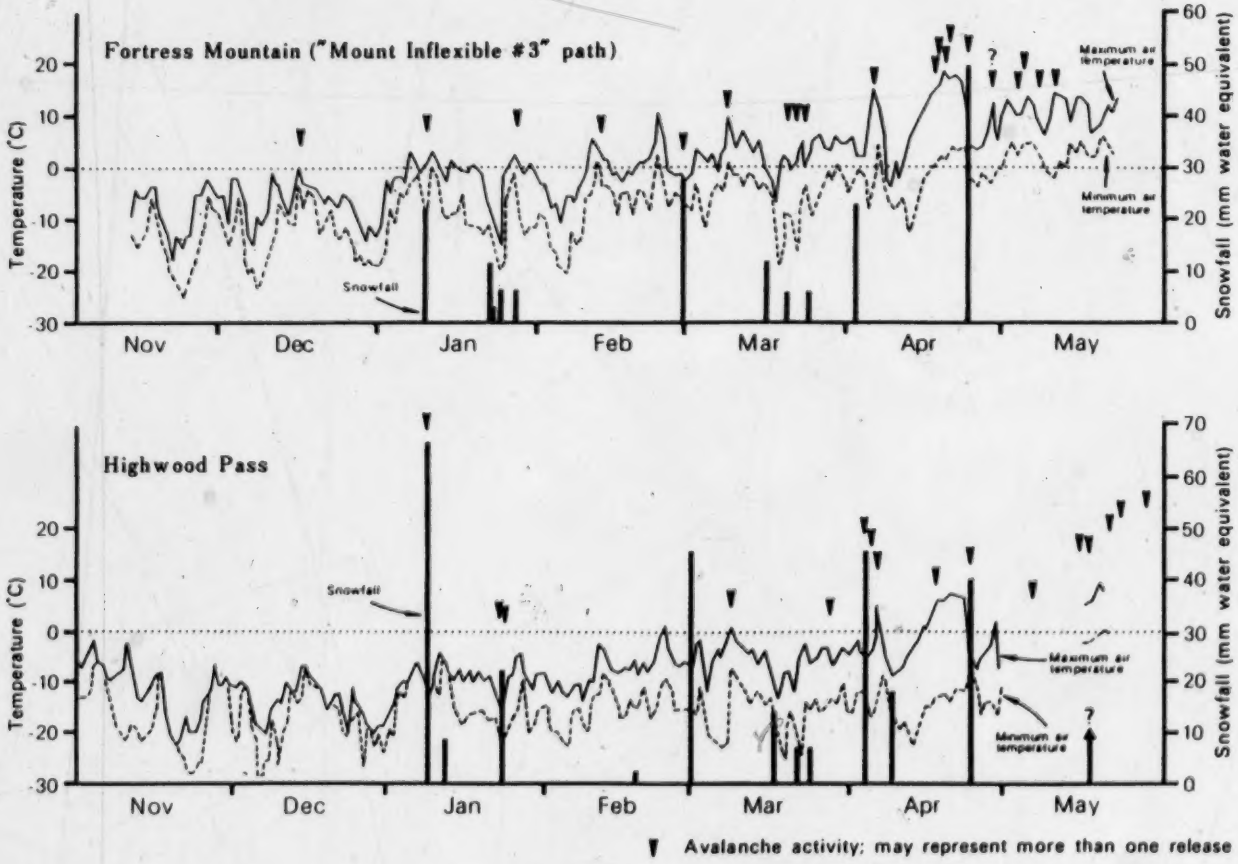


Figure 5.1 Snowfall, maximum/minimum air temperatures and avalanche activity, 1982-83

the total both on Mount Inflexible #3 and at Highwood Pass- were triggered by a composite mechanism of snowfall followed by a rise in air temperatures. In fact, avalanches triggered in this way were more numerous on the Mount Inflexible #3 path than ones triggered by snowfall only. Such situations were conspicious because the warming and subsequent melting occurred before the new snow had a chance to consolidate and gain strength.

During the winter of 1982-83 wind played a secondary but nevertheless important role as an avalanche trigger, occurring in conjunction with snowfall. In the following sections it is treated as a distinct trigger mechanism in order to describe its characteristics more clearly.

Distinctive types of avalanches were associated with each trigger mechanism. Snowfall with wind usually produced soft slab avalanches as determined from a comparison of wind data and the avalanche record (Table 3.1), whereas snow falling in calm conditions resulted in dry, loose snow avalanches. Thaw triggering usually produced wet snow avalanches, although whether they possessed loose snow or slab characteristics was difficult to distinguish (compare the 'MOISTURE CONTENT' and 'TYPE' columns in Table 3.1).

Even though the same types of avalanche triggers operated in both study areas, their lack of synchronousness reflected the lack of regional uniformity in mountain weather patterns and climate, discussed by Barry (1981. See Chapter 1 and Figure 5.2). The occurrence of snowfall triggered avalanches varied widely between the two paths, except for those caused by major storms (9-10 January and 24-25 April). This lack of agreement emphasizes the weakness of a regional avalanche hazard evaluation based on information from only one or two study sites. A closer temporal relationship was present between thaw triggered avalanches on the two paths, due to the similarity in air temperature trends although not in actual temperatures, over the winter (Figures 2.3 and 5.2).

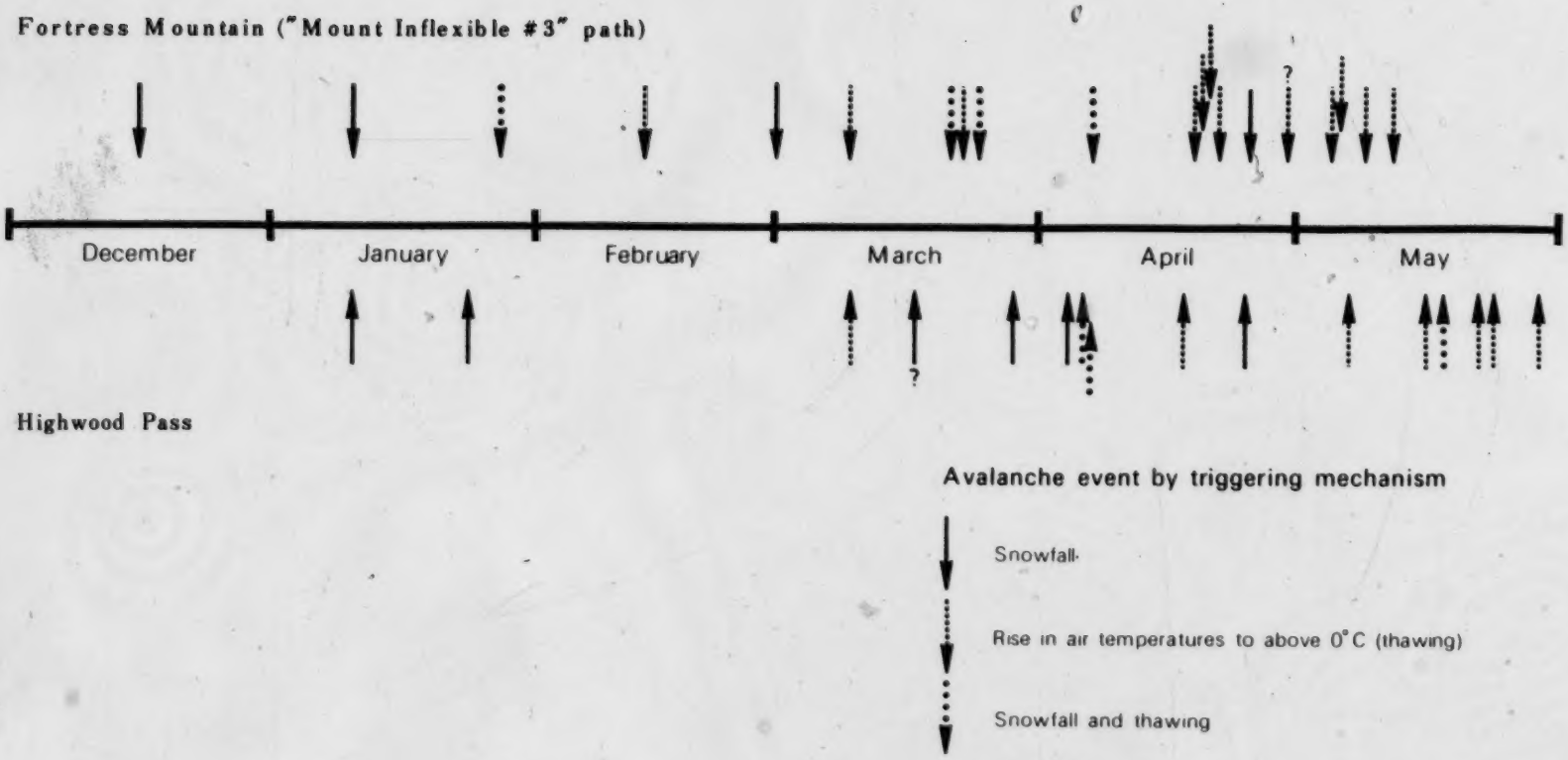


Figure 5.2 Comparison of avalanching between Fortress Mountain and Highwood Pass, 1982-83

5.1 Snowfall

Snowfall triggered latent instability in older snow layers by the addition of load to the snowpack. Hence the avalanches produced were load-induced releases (LaChapelle and Armstrong, 1976). Failure in some cases occurred at the old-new snow interface (Chapter 4): in these situations the snowfall triggered an instability present at the old snowpack surface (i.e. crust).

On the Mount Inflexible #3 path, snowfalls of 22 mm (10 January), 27 mm (28 February-1 March) and 50 mm (24-25 April) water equivalent triggered several size 2-3, one probable size 2 and several size 3-4 avalanches respectively (Table 3.1).

At Highwood Pass, snowfalls of 67 mm (9-10 January), 23 mm (23-24 January), 45.5 mm (3-4 April) and 40 mm (24-25 April) water equivalent triggered several size 2-3, one size 2 and size 3, several size 2-3 and three to four size 2-3 avalanches respectively. In addition, the 9-10 January snowfall triggered a size 3 avalanche on the Highwood Pass #5 path, which deposited snow and broken timber on Highway 40. The 24-25 April storm triggered a large (size 4) avalanche on the Highwood Pass #2 path, which crossed Highway 40. The avalanche deposit was measured to be 50 m in width, 130 m in length and 4 m in depth; it took several weeks before the highway could be reopened to maintenance crews (Plate 5.1). This snowfall also triggered numerous other large avalanches on slopes of all aspects in the Highwood Pass area.

The above information on snowfall totals that triggered avalanches can be compared to thresholds established by other researchers. The effect of wind on the avalanche paths is not taken into account, since no quantifiable data are available on the additional wind loading of snow. In the Colorado Front Ranges and the Wasatch Mountains of Utah approximately 25-30 mm water equivalent of new snow is required for large avalanches (U.S. Forest Service, 1953; Borland, 1954; Judson, 1967; LaChapelle, 1967; Perla, 1970). Judson (1967) however notes that only 10 cm of new snow is necessary for avalanching in the Colorado Front Ranges if its deposition is accompanied by wind. Schaerer (1962) has observed a lower threshold of 25-40 cm of new snow for avalanches reaching the highway at Rogers Pass, British Columbia; exact values are dependent on wind conditions. De Quervain (1975) feels that 50 cm of new snow per day in the Swiss Alps merits special attention with regard to hazard development. Perla's

Plate 5.1 Size 4 soft slab avalanche on the "Highwood Pass #2" path. Release occurred on 25 April 1983.

(1970) research in Utah also indicates that 50 mm water equivalent of new snow within a 24-hour period will produce intense avalanche activity.

The minimum snowfall total that triggered avalanches of significant size (size 2 or larger) in the study areas in 1982-83 was 22 mm water equivalent, (22 cm of snow, assuming a new snow density of 100 kg m^{-3}), which agrees loosely with the lower thresholds of the other authors. However, this figure must be regarded as inconclusive because it is based on only seven snowfalls. In addition, snowfall data gathered at a sheltered study site must be used with caution when evaluating developing avalanche conditions. Judson (1967) found starting zones at Berthoud and Loveland Passes in Colorado to contain two to three times greater depths of new snow than nearby sheltered study sites. This type of relationship was observed in 1982-83 at Highwood Pass; after the storm of 24-25 April a soft slab crown face approximately one metre high was observed on a northeast-facing slope (Plate 3.5) while the study site indicated only 40 cm of new snow. Since this avalanche resulted from a lack of cohesion at the old-new snow interface (Appendix 3), the one metre must represent the depth of new snow deposition on the avalanche slope.

Precipitation intensity (the product of snowfall intensity and snow density) is perhaps a more significant parameter than snowfall total in the development of avalanche hazard (see Chapter 1). A high precipitation intensity (P.I.) was noted earlier to be also one of the prime requirements for soft slab formation.

Atwater's (1952; 1966) observations at Alta, Utah indicate that with a P.I. continuously over 2.5 mm h^{-1}, accompanied by wind speeds averaging 6.7 m s^{-1} or over, and in the absence of sluffing , a high degree of avalanche hazard is present when total precipitation amounts equal 25 mm. LaChapelle's (1967) research at Alta produces comparable values. Perla (1970) concurs, but notes that a snowfall intensity of only 15 mm h^{-1} (a P.I. of approximately 1,5 mm h^{-1}) is sufficient for avalanching when wind speeds exceed a 'critical' (snow transport threshold) level. At Berthoud and Loveland Passes in Colorado Perla feels that a snowfall intensity of only 10 mm h^{-1} (a P.I. of approximately 1.0 mm h^{-1}) can produce instability, even in the absence of wind. With wind speeds exceeding 4.2 m s^{-1} a snowfall intensity of only 6.0 mm h^{-1} (a P.I. of approximately 0.6 mm h^{-1}) is required. In the Swiss Alps de Quervain (1975) observed that at high

snowfall intensities of 50-100 mm h^{-1} (P.I. of approximately 5.0-10.0 mm h^{-1}) stability can become critical on slope angles of only 25°.

By dividing the precipitation totals of storms by their approximate duration (as recorded on the time-lapse record) a rough estimate of P.I. was obtained for snowfalls at Fortress Mountain and Highwood Pass. At Fortress Mountain, P.I.s were approximately 1.8 mm h^{-1} for the 10 January storm, 2.3 mm h^{-1} for the 28 February-1 March storm, and 2.1 mm h^{-1} for the 24-25 April storm. At Highwood Pass P.I.s were approximately 3.7 mm h^{-1} for the 9-10 January storm, 1.0 mm h^{-1} for the 23-24 January storm, 1.3 mm h^{-1} for the 3-4 April storm, and 1.7 mm h^{-1} for the 24-25 April storm. Almost all were accompanied by winds which presumably increased P.I.s on the avalanche paths (Plate 1.3). However, if additional wind loading is disregarded it can be seen that relatively low P.I.s of 1.0 mm h^{-1} and 1.3 mm h^{-1} at the Highwood Pass study site produced significant avalanching (Table 3.1). The poor cohesion of new snow to the old snow surface, such as during the 3-4 April storm at Highwood Pass (Appendix 3), may have been the cause of this.

5.2 Air Temperature

Long term air temperature patterns determine the types of metamorphic changes that occur in a seasonal snowcover, and in this way affect levels of snowpack instability. However, sudden (i.e. over one or two days) rises in air temperature to above 0°C can act as avalanche triggers, by destroying snow cohesion and triggering failure. Heating of the surface layers of the snowpack takes place through convection and conduction (a radiation component is also present in sunny conditions). The result is destruction of intergranular bonding and the introduction of free water into the snowpack. Failure of the pack will take place if the wet snow becomes incohesive enough or the meltwater erodes the bond between the saturated layers and any underlying crust or the ground. It can be argued in this instance that air temperature (thawing) increases instability (by reducing the strength of the snow rather than increasing stresses on it). However, it is convenient to class such rises in air temperature as avalanche triggers, since they ultimately cause the avalanche, and often exploit existing snowpack instabilities (e.g. a buried crust) to produce failure.

Armstrong (1976) has observed in the San Juan Mountains of Colorado that once the entire study site snowpack reaches a temperature between -2.0°C and 0°C, the next period of warmer air temperatures is much more critical for thaw triggered avalanching than previous periods of similar temperatures when the snowpack was still under subfreezing conditions. However, avalanches do not actually occur in great numbers until mean daily air temperatures at the study site exceed 0°C. Schaerer (1962) notes that at Rogers Pass, British Columbia, avalanches will occur on the first or second day after the mean daily air temperature reaches 0°C, if the entire snowpack is isothermal.

Rises in air temperature to above 0°C at Fortress Mountain and Highwood Pass triggered surface layers of snow into motion in March and April of 1983. Later in the spring (April - May) however as the snowpack approached isothermal conditions, warm air temperatures triggered in some cases avalanches that incorporated snow all the way to the ground surface ('full depth' avalanches; Table 3.1).

Since rises in air temperature trigger avalanches by decreasing snowpack strengths through melting, it would be expected that avalanches triggered in this way are composed of wet snow. A comparison of Figure 5.3 and Table 3.1 shows all thaw triggered avalanches on the Mount Inflexible #3 path and at Highwood Pass to have been wet snow avalanches. The mean daily air temperature curve from the Fortress Mountain study site correlates well with such avalanches on the Mount Inflexible #3 path (Figure 5.3), with the first release occurring on 13 February. In all cases mean daily air temperatures during avalanching were above 0°C, which agrees with Armstrong's (1976) and Schaerer's (1962) observations.

A similar relationship between mean daily air temperatures and thaw triggered avalanches was found to exist at Highwood Pass (Figure 5.3), with the first release occurring on 9 March. On the two days (9 March and 17 April) that thaw triggered avalanches took place but mean daily air temperatures did not reach 0°C, the daily maximum nevertheless rose above freezing (Figure 5.1).

Maximum daily air temperatures during thaw triggered avalanching ranged from 0.5°C to 16.5°C, with the maximum value being recorded at the Fortress Mountain study site on 20 April. The most dramatic series of thaw triggered wet snow avalanches occurred on the Mount Inflexible #3 path on 21 April (Table 3.1), when maximum air

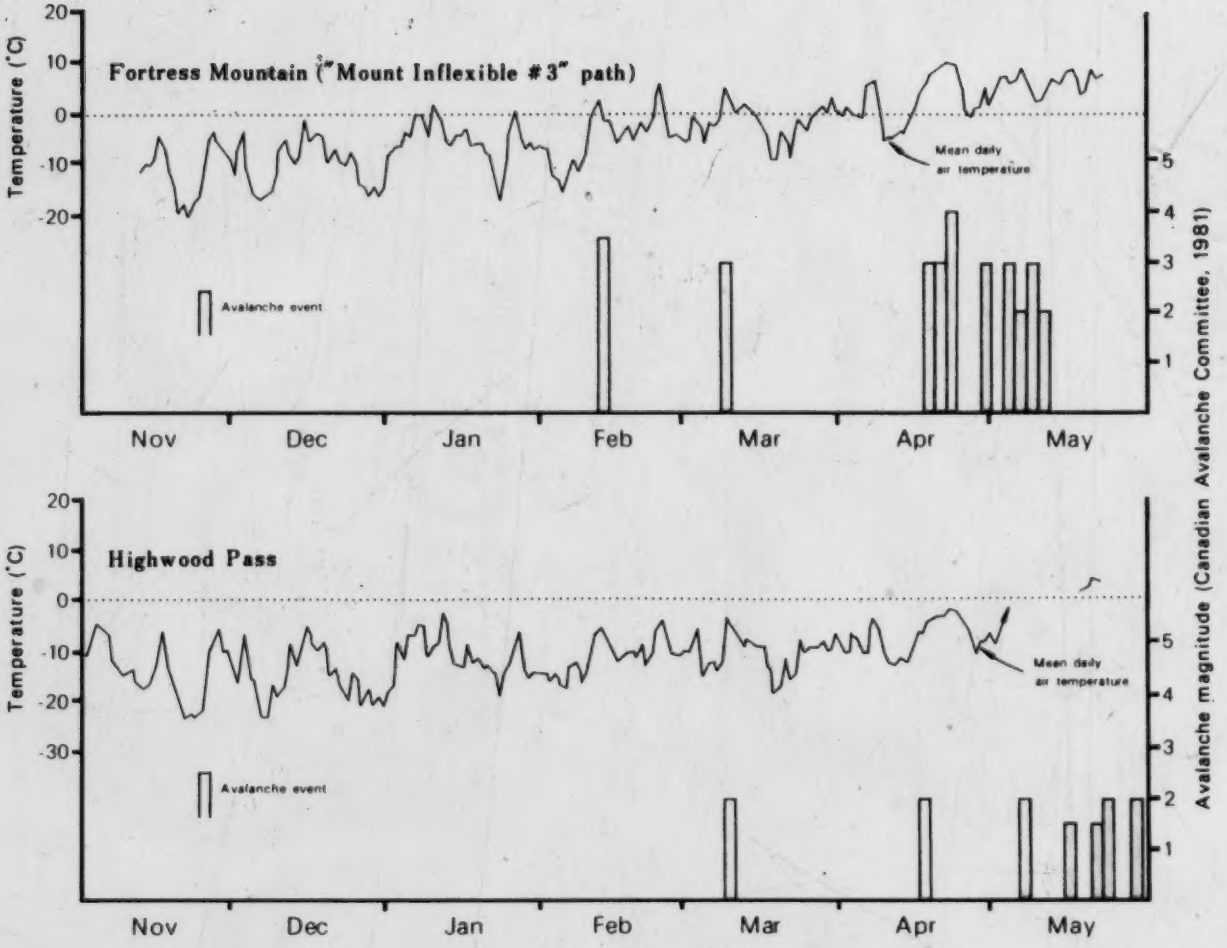


Figure 5.3 Mean daily air temperatures and thaw triggered avalanches by magnitude, 1982-83

temperatures of 15.5°C triggered seven avalanches ranging in size from 2 to 4. It is worthwhile to note the very warm air temperatures during the preceding week (Figure 5.1) which greatly weakened the snowpack.

Higher air temperatures in the Fortress Mountain area were the primary reason for larger numbers of thaw triggered avalanches on the Mount Inflexible #3 path than at Highwood Pass. However, the morphology of the Mount Inflexible path probably had some effect: whereas both it and the Highwood Pass slope have a northeasterly aspect, the shallow cirque shape of Mount Inflexible #3 (Plate 1.4) allowed direct insolation to strike the northwest flank for much longer periods of time. As a result, the great majority of thaw triggered avalanches originated on this side of the starting zone and upper track.

5.3 Wind

Wind acts in two ways to trigger avalanches: it loads lee slopes with additional snow and consolidates the deposited snow into slabs (see Chapter 3; soft slab avalanches). It thus acts in close association with snowfall to trigger load-induced avalanches.

The effect of wind is significant on the monitored avalanche paths because of their lee slope character, and this was reflected in 1982-83 by a number of soft slab avalanches (Figure 3.1 and Table 3.1). Not enough data are available, however, to identify the precise effects of wind on such avalanche activity, although some general observations can be made.

Two of the three snowfalls that triggered soft slab avalanche activity on the Mount Inflexible #3 path (16 December and 28 February-1 March) were accompanied by "moderate" (Appendix 1) winds. The event for which wind information is not available (24-25 April) produced crown fractures in the starting zone that were clearly visible on later examination (Plate 3.5).

At Highwood Pass, three out of the four snowfalls that triggered soft slab avalanches (9-10 and 23-24 January and 24-25 April) were observed to be associated with westerly winds, although their strength is unknown. The 3-4 April storm for which winds were not observable produced extensive cornices at the crest of the starting zone of the monitored slope. Not only do these indicate westerly winds during the storm, but

utilizing the absolute minimum wind speed of 7 m s^{-1} necessary for cornice formation (Montagne *et al*, 1968), they also indicate winds sufficient for soft slab formation (based on Atwater's [1966] 6.7 m s^{-1} and LaChapelle's [1967] 7.0 m s^{-1} lower thresholds). Well developed crown fractures provided additional evidence of soft slab formation during the 24-25 April storm (Plates 3.6 and 3.7).

Given the critical requirements of snowfall and wind, soft slab has a propensity to form under relatively warm conditions. Judson (1967) identified an air temperature threshold of -12.0°C in Colorado above which soft slab would form, assuming other favourable conditions such as intense snowfall and moderate winds. Soft slab avalanches on the Mount Inflexible #3 path and on the Highwood Pass slope in 1982-83 released during mean daily air temperatures at the study sites ranging from 0°C to -14.8°C, with a mean of -6.2°C.

5.4 Composite Trigger Mechanisms

Snowfall followed by thawing was a distinct composite trigger observed in 1982-83. It was distinguished from snowfall and from rises in air temperature alone by being any snowfall that was followed within three days (after which new snow will normally have settled and sintered significantly in all but very cold weather [Perla and Martinelli, 1976]) by a rise in air temperature to or above 0°C. This type of thaw induced instability in unconsolidated new snow has also been reported by other authors (e.g. Schaerer, 1967).

A combination of snowfall and warm temperatures is an especially important avalanche trigger in spring, when both snowfalls and rises in temperature are of a greater magnitude. Avalanche activity can result even if releases had taken place during the storm. For example, the 3-4 April snowfall at Highwood Pass triggered soft slab avalanches during the storm, and moist and wet snow releases in the same locations one and two days later when air temperatures rose (Table 3.1).

At Fortress Mountain the first snowfall-thaw triggered avalanche occurred on 27 January, with only 6 mm water equivalent of snowfall (but with additional wind loading) and a subsequent air temperature maximum of 2.0°C triggering three size 2 avalanches. On 20-21 March, 18 mm water equivalent of snowfall and a temperature maximum of 0°C

triggered a size 1 / 2 avalanche. An additional 6 mm water equivalent of new snow and a temperature maximum of 0°C on 24 March triggered a size 2 / 3 avalanche. The last avalanche triggered by the snowfall-thaw mechanism took place on 6 April, when 23 mm water equivalent of new snow and a temperature maximum of 13.5°C produced a size 3 release.

The first snowfall-thaw triggered avalanche at Highwood Pass was a sluff on 5 April, resulting from an air temperature maximum of -4.0°C following 45.5 mm water equivalent of snowfall on 3-4 April. The fact that study site temperatures did not reach 0°C but still managed to trigger an avalanche, albeit a small one, illustrates the role of avalanche path aspect in avalanche formation. The time-lapse record indicates sunlit conditions on the avalanche slope for most of the morning when the study site would have been in shade, and at this time of year it seems conceivable that sufficient heat would have been generated in the surface layers of the snowcover on the slope to result in at least some weakening of the new, unconsolidated snow. The sluff released adjacent to a rock outcrop, and thus an increase in tensile strain may also have been a factor (Plate 3.4).

The 3-4 April snowfall was again triggered into motion on 6 April, when a temperature maximum of 4.5°C produced a size one and size two avalanche. Thawing on this day also triggered a size 3 / 4 avalanche on the Highwood Pass #5 path, which stopped 100 m above Highway 40; the avalanche deposit measured 60 m in width, 250 m in length and 1.5 m in height (Plate 5.2).

The last snowfall-thaw triggered avalanche occurred at Highwood Pass on 17 May, when a snowfall (total water equivalent unknown) was subsequently followed by a temperature maximum of 5.0°C, triggering a sluff.

Mean daily air temperatures during snowfall-thaw triggered avalanches ranged from -11.0°C (5 April at Highwood Pass) to 5.0°C (6 April at Fortress Mountain), which are lower than those means associated with thaw triggered avalanches of older snow (-5.0°C to 9.0°C). This implies that new, unconsolidated snow required less heating and melting than older snow to trigger failure, as a result of the lack of intergranular bonding. This is reinforced by the moist rather than wet nature of some of the snowfall-thaw triggered avalanches (27 January and 20-21 March on Mount Inflexible #3; 5 April at Highwood Pass).

Plate 5.2 Size 3/4 wet snow avalanche on the "Highwood Pass #5" path. Release occurred on 6 April 1983.

5.5 Summary

All avalanches recorded in 1982-83 on the Mount Inflexible #3 path and at Highwood Pass were triggered by weather events.

The most important weather triggers were snowfall and rises in air temperatures to above 0°C. Snowfall triggered load-induced avalanches, whereas thawing triggered avalanches by decreasing the strength of the snowcover.

Wind was an important secondary trigger acting in conjunction with snowfall. It had the dual effect of increasing snow deposition on the lee-facing monitored avalanche slopes and of consolidating the new snow into slabs. These conditions produced soft slab avalanches, which had a propensity to occur in air temperatures not far below freezing. In the absence of wind, snowfall tended to trigger dry, loose snow avalanches, although these were rare.

Thaw triggered avalanches were all composed of wet snow, reflecting the significant amount of melting of intergranular bonds that had occurred before failure. Mean daily air temperatures were 0°C or above during most such wet snow avalanche days.

Warm weather immediately following a snowfall was another triggering mechanism in 1982-83, being particularly important in spring when both snowfalls and rises in air temperature were of a higher magnitude. Mean daily air temperatures during snowfall-thaw triggered avalanching were lower than during thaw triggered avalanching of older snow, reflecting the unconsolidated nature of the new snow.

The lack of uniformity in the regional mountain climate of Kananaskis Country was reflected in the poor synchronousness of avalanche triggering weather events between the study areas, even though the same triggers operated in both. Although major storms and general air temperature trends exhibited relatively good correlations between the two, the lack of conformity in smaller but nonetheless significant weather patterns (and resulting avalanches) has important implications; a lack of avalanche activity in one part of Kananaskis Country does not necessarily mean another part is also free of hazard.

6. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this research was to 1) develop and test a time-lapse photography system for continuously monitoring avalanche paths, and 2) use the information obtained from such a record to aid in determining the types and causes of avalanching in two areas in Kananaskis Country, Alberta during the winter of 1982-83.

The time-lapse camera systems filmed two avalanche paths continuously and successfully over the entire winter. They provided a large body of data on avalanche occurrence, type, size, distance of travel, and on weather conditions during release. Additional weather information was also obtained from the films. Some limitations of the systems surfaced as the study progressed, but these were relatively minor technical ones.

Weather to a large degree determined the clarity of the avalanche record. Snowfall-triggered avalanche activity was only evident after storms, since visibility was very poor during the avalanche events. On the other hand, thaw triggered avalanches were vividly recorded on film, since the weather conditions were good and the avalanches could be 'seen' from one frame to the next.

The avalanche records indicate that both paths were active over the entire winter season. On the Mount Inflexible #3 path, twenty-nine avalanche events were recorded, while twenty-one were recorded on the Highwood Pass slope. The numbers are in reality even higher, because these figures assign only one avalanche to events where an unknown number of multiple releases occurred. The recorded avalanches ranged in size from sluffs to large size 4 avalanches.

Three types of avalanches were identified on the time-lapse films. These were wet snow, soft slab and dry, loose snow avalanches. Wet snow and soft slab avalanches were dominant, with wet snow avalanches especially numerous in the spring. As a result, the bulk of the winter's avalanche activity occurred at this time. Dry, loose snow avalanches were only recorded during two storms, and were of relatively low magnitude. Hard slab avalanches, noted by some authors to be an important source of hazard in the Rocky Mountains (e.g. LaChapelle, 1966), were not recorded in 1982-83.

The development of snowpack structure in 1982-83, as observed at two snow study sites, followed the general seasonal evolution of a snowpack in a cold subhumid continental climate. Short-term temperature and precipitation trends however modified

this development to some degree.

The pattern and sources of snowpack instability at both study sites in 1982-83 closely reflected the development and structure of the snowcover. Early in the winter, depth hoar grains in the basal layers of the snowpack provided a source of instability. Their influence however was diminished as warmer weather and a thicker snowcover later in the winter caused a shift from temperature gradient to equi-temperature metamorphism. At Highwood Pass at least, this shift had a stabilizing influence on the snowpack. High levels of instability in the spring coincided with the development of complex stratigraphies of new snow layers, grainy old snow and melt-freeze crusts in the upper part of the snowcover, which provided numerous layers and layer interfaces weak in shear. On attaining an isothermal condition, the snowpacks became extremely noncohesive and unstable as a result of the destruction of intergranular bonding.

The examination of avalanche failure planes at both study sites over the winter indicated a seasonal progression of failure in depth hoar or at the old-new snow interface in early and midwinter, to failure in complex upper snowpack stratigraphies in the spring. Almost all of the failure planes that were located occurred at the interfaces of distinct and cohesive layers. Lubricating layers at these failure planes were rare.

All avalanches on the monitored paths in 1982-83 were triggered by weather events. Spontaneous 'climax' avalanches, triggered by gradual adverse metamorphism of the snowpack, were not identified.

Snowfall and rises in air temperature to above 0°C were the predominant trigger mechanisms. Whereas snowfall increased snowpack stresses, rises in air temperature decreased snowpack strengths through the melting of intergranular bonds. Avalanches triggered by the latter mechanism were all composed of wet snow.

Wind played a secondary but nevertheless important role as an avalanche trigger, occurring in conjunction with snowfall to increase new snow totals and snowfall intensities, and producing soft slab avalanches. On the rare occasion that snow fell in calm conditions, the triggered avalanches consisted of dry, loose snow.

A combination of snowfall and subsequent warm temperatures triggered many of the recorded avalanches. This distinct composite trigger was especially important in the spring, when heavy snowfalls were accompanied by warm weather. Rises in air

temperature however were of a lower magnitude than those required for avalanching of older snow layers, indicating that cohesion in unconsolidated new snow was easily destroyed.

Even though the same avalanche triggering mechanisms operated in the two study areas, they displayed a lack of temporal synchronousness. This was especially evident with snowfall triggered avalanches, which except for those associated with major storms, showed a very poor correlation between the two areas. Avalanches triggered by rises in air temperature compared more closely between the two paths, due to the similarity in air temperature trends over the winter between the Fortress Mountain and Highwood Pass study areas. Lower average temperatures at Highwood Pass, however, resulted in less thaw triggered avalanching there than on the Mount Inflexible #3 path.

This study has demonstrated that time-lapse photography can be a cheap and effective way of continuously monitoring avalanche activity. The results also indicate that avalanche paths are more active than is commonly thought. Much of the previous research on avalanche frequencies has been based on dendrochronological techniques, and this is especially the case in Kananaskis Country. These techniques, however, have severe limitations because they can only estimate the return intervals of past avalanches large enough to have travelled into the runout zones of the paths and damaged trees (e.g. Steel, 1982; McPherson *et al*, 1983), and moreover can only record the occurrence of one avalanche event per winter. The time-lapse results showed that both monitored paths experienced a large number of smaller avalanches that were not spectacular, and would not be reflected in dendrochronological records, but which nevertheless are life threatening.

The two dominant types of avalanches - wet snow and soft slab - reflect the importance of snowfalls and springtime air temperature rises in the triggering of avalanches. The number of dry, loose snow avalanches that were recorded was probably somewhat higher, because their characteristically small size makes them difficult to record. Nevertheless, their small number (and size) can probably be explained by Judson's (1967) observation that deep snowfalls are often accompanied by winds, which create slabs.

The character of snowpack development, snowpack instability and failure planes were found to be closely related, with the last two reflecting the structure of the snowcover over the winter. The examination of actual failure planes provided a valuable insight into the nature of snowpack weaknesses that failed and produced avalanches. Their location at the interfaces of distinct and cohesive layers implies that low shear strength at a layer interface was more conducive to failure than weakness within a layer. The small number of lubricating layers that were identified indicates that they were not necessary for failure to occur.

The need for some kind of weather event to trigger avalanches in the study areas in 1982-83 reinforces the view of many authors (e.g. LaChapelle, 1970; Armstrong and Ives, 1976) that even in continental climates, where the snowpack is often structurally much weaker than in a coastal mountain environment, the triggering of latent instability requires such a weather trigger. It is important to note, however, that such triggering can be accomplished artificially and even more efficiently by backcountry tourists. The poor synchronousness of some avalanche triggering weather events between the two study areas reflects the lack of regional uniformity which is characteristic of mountain weather and climate. This severely handicaps any general avalanche hazard evaluation for a large region such as the Kananaskis.

The results of this study have thus allowed an insight into the nature and causes of avalanching in Kananaskis Country. More research is needed to determine whether these results accurately represent long-term conditions in the region, although weather records indicate that 1982-83 was a reasonably typical winter in the Kananaskis.

With regard to recommendations for future research, there is room for further refinement of the time-lapse slope monitoring system. Particularly useful would be an examination of ways to obtain a better avalanche record in conditions of poor visibility, and of ways to improve the image resolution for the recording of low magnitude avalanche activity. These would very likely necessitate the use of more sophisticated (although not prohibitively expensive) camera equipment. Certainly large-format film (16 or 35 mm), and perhaps even infra-red film, will produce better results. The use of two or more cameras on one path, filming it from different vantage points, may also provide a clearer record of avalanche activity. In fact, with a sufficient number of cameras,

time-lapse photography could even be used to provide a continuous record of snowpack depths, by filming a calibrated stake, or by mounting a camera vertically, a precise and continuous record of cloud movement (i.e. wind direction) could be obtained.

There are several ways in which further contributions can be made to understanding the causes of avalanches in Kananaskis Country. Most importantly, a project utilizing an approach similar to this study should ideally be carried out over a period of several years, in order to obtain data on long-term conditions. Also, the examination of snowpack conditions in avalanche starting zones would yield valuable information on instabilities that are weak enough to fail under a triggering force. The problem of entering the starting zones of large avalanche paths could be overcome by initiating avalanches on safer small slopes which are representative of conditions on the large paths.

The reliability of weather and snowpack data that are collected can be enhanced by utilizing study sites that are as closely representative as possible of conditions on the avalanche paths. To this end, the usefulness of any such study site in Kananaskis Country can be increased by locating it so that its elevation, exposure (particularly important in the spring when thaw triggered avalanches are common) and especially snow loading characteristics (with regard to wind transported snow) are similar to that of the path it represents. Such an ideal situation is unfortunately often difficult to achieve in the region because of the lack of level ground at higher elevations.

REFERENCES

Adams, E.E. and Brown, R.L.
1982: Further results on studies of temperature gradient metamorphism (short note); *Journal of Glaciology*, v. 28, no. 98, p. 205-210.

Akitaya, E.
1967: Some experiments on the growth of depth hoar; in *Physics of Snow and Ice, Proceedings of the International Conference on Low Temperature Science, 14-19 August 1966, Sapporo, Japan*; v. 1, pt. 2, p. 713-724.

Akitaya, E.
1973: Observations of avalanches with a video-tape recorder; *Teion Kagaku*, Series A, v. 31, p. 287-289.

Alberta Recreation and Parks
1977: *Policy for Recreation Development of Kananaskis Country*; Government of Alberta Publication, Edmonton, 36 p.

Alberta Recreation and Parks
1978: *Kananaskis: Alberta's First Mountain Provincial Park*, Information Bulletin Parks Division, Edmonton, 4 p.

Alberta Recreation and Parks
1983: Minutes, Snow Management Committee; Government of Alberta.

Ambach, W. and Howorka, F.
1966: Avalanche activity and free water content of snow at Obergurgl (1980 m a.s.l., spring 1962); in *International Symposium on the Scientific Aspects of Snow and Ice Avalanches, 5-10 April 1965, Davos, Switzerland*; International Association of Scientific Hydrology Publ. no. 69, Gentbrugge, Belgium, p. 65-72.

Anderson, D., FitzGerald, L., Hoopingarner, K. and Stratton, J.
1978: Avalanche control and hazard forecasting techniques; in *Avalanche Control, Forcasting (sic), and Safety, Proceedings of a Workshop Held in Banff, Alberta 1-4 November 1976*, ed. R. Perla; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 120, Ottawa, p. 2-18.

Armstrong, R.L.
1976: Wet snow avalanches; in *Avalanche Release and Snow Characteristics, San Juan Mountains, Colorado*, ed. R.L. Armstrong and J.D. Ives; Institute of Arctic and Alpine Research Occasional Paper no. 19, University of Colorado, Boulder, p. 67-82.

Armstrong, R.L.
1980: An analysis of compressive strain in adjacent temperature-gradient and equitemperature layers in a natural snow cover; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 283-290.

Armstrong, R.L.
1981: Some observations on snow cover temperature patterns; in *Proceedings of Avalanche Workshop, 3-5 November 1980, Vancouver, B.C.*, ed. Canadian Avalanche Committee; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 133, Ottawa,
p. 66-81. Technical Memorandum no. 133, Ottawa, p. 66-81.

Armstrong, R.L. and Armstrong, B.L.
1981: *San Juan Mountains Avalanche Study: Evaluation and Prediction of Avalanche Hazard; Meteorological and Avalanche Observations 1980-1981*; Institute of Arctic and Alpine Research Final Report Nov. 1980 - Oct. 1981, University of Colorado, Boulder, 27 p.

Armstrong, R.L. and Ives, J.D., ed.
1976: *Avalanche Release and Snow Characteristics, San Juan Mountains, Colorado*; Institute of Arctic and Alpine Research Occasional Paper no. 19, University of Colorado, Boulder, 256 p.

Armstrong, R.L. and LaChapelle, E.R.
1976: Avalanche forecast methods; in *Avalanche Release and Snow Characteristics, San Juan Mountains, Colorado*, ed. R.L. Armstrong and

J.D. Ives; Institute of Arctic and Alpine Research Occasional Paper no. 19, University of Colorado, Boulder, p. 41-65.

Armstrong, R.L., LaChapelle, E.R., Bovis, M.J. and Ives, J.D.
1974: *Development of Methodology for Evaluation and Prediction of Avalanche Hazard in the San Juan Mountain Area of Southwestern Colorado*; Institute of Arctic and Alpine Research Occasional Paper no. 13, University of Colorado, Boulder, 141 p.

Atmospheric Environment Service
1982: *Canadian Climate Normals: Wind, 1951 - 1980*, v. 5, Environment Canada.

Atwater, M.M.
1952: The relationship of precipitation intensity to avalanche occurrence; in *Proceedings of the 20th Annual Meeting of the Western Snow Conference, 21-22 April, Sacramento*, p. 11-19.

Atwater, M.M.
1966: The relationship of precipitation intensity to avalanche occurrence; in *Proceedings of the 34th Annual Meeting of the Western Snow Conference, 19-21 April, Seattle*, p. 11-19.

Bader, H., Haefeli, R., Bucher, E., Eckel, O. and Thams, Ch.
1939: *The Snow and It's Metamorphism*; Bern, Switzerland, Snow, Ice and Permafrost Research Establishment Translation no. 14.

Baig, M.N.
1972: *The Ecology of Timberline Vegetation in the Rocky Mountains of Alberta*, unpub. Ph.D. thesis, University of Calgary, Calgary, 444 p.

Bakkehøi, S., Cheng, T., Domaas, U., Lied, K., Perla, R. and Schieldrop, B.
1981: On the computation of parameters that model snow avalanche motion; *Canadian Geotechnical Journal*, v. 18, no. 1, p. 121-130.

Ballard, G.E.H. and McGaw, R.W.
1966: A theory of snow failure; in *International Symposium on the Scientific Aspects of Snow and Ice Avalanches, 5-10 April 1965, Davos, Switzerland*; International Association of Scientific Hydrology Publ. no. 69, Gentbrugge, Belgium, p. 160-169.

Banner, J.A. and van Everdingen, R.O.
1979: *Automatic Time-Lapse Camera Systems*; National Hydrology Research Institute Paper no. 4 (Inland Waters Directorate Technical Bulletin no. 112), Ottawa, 20 p.

Barry, R.G.
1981: *Mountain Weather and Climate*; Methuen, New York, 313 p.

Bergen, J.D.
1980: A slip-velocity hypothesis applied to hydraulically smooth wind flow over a snow cover; in Symposium on Snow in Motion, Colorado, 12-17 August; *Journal of Glaciology*, v. 26, no. 94, p. 447-452.

Björnsson, H.
1980: Avalanche activity in Iceland, climatic conditions, and terrain features; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 13-24.

Bois, P. and Obled, C.
1972: *Analyse des données nivoclimatologiques en vue de la prévision des avalanches*; Weissfluhjoch-Davos, Eidg. Institut für Schnee-und Lawinenforschung; Grenoble, Institut National Polytechnique de Grenoble.

Bois, P., Obled, C. and Good, W.
1975: Multivariate data analysis as a tool for day-by-day avalanche forecasting; Symposium. *Mécanique de la neige. Actes du colloque de Grindelwald, avril 1974*; International Association of Scientific Hydrology Publ. no. 114, p. 391-403.

Borland, W.M.
1954: *Investigation of snow conditions causing avalanches*; Interim Report no. 3, U.S. Army Corps of Engineers, Denver.

Bovis, M.J.
1974: Statistical analysis; in *Development of Methodology for Evaluation and Prediction of Avalanche Hazard in the San Juan Mountain Area of Southwestern Colorado*, R.L. Armstrong, E.R. LaChapelle, M.J. Bovis

and J.D. Ives; Institute of Arctic and Alpine Research Occasional Paper no. 13, University of Colorado, Boulder, p. 71-94.

Bovis, M.J.
1976: Statistical analysis; in *Avalanche Release and Snow Characteristics, San Juan Mountains, Colorado*, ed. R.L. Armstrong and J.D. Ives; Institute of Arctic and Alpine Research Occasional Paper no. 19, University of Colorado, Boulder, p. 83-130.

Bovis, M.J.
1977: Statistical forecasting of snow avalanches, San Juan Mountains, Southern Colorado, U.S.A.; *Journal of Glaciology*, v. 18, no. 78, p. 87-99.

Bradley, C.C.
1970: The location and timing of deep slab avalanches; *Journal of Glaciology*, v. 9, no. 56, p. 253-261.

Bradley, C.C. and Bowles, D.
1967: Strength-load ratio: an index of deep slab avalanche conditions; in *Physics of Snow and Ice, Proceedings of the International Conference on Low Temperature Science, 14-19 August 1966, Sapporo, Japan*; v. 1, pt. 2, p. 1243-1254.

Bradley, C.C., Brown, R.L. and Williams, T.R.
1977: Gradient metamorphism, zonal weakening of the snow-pack and avalanche initiation; *Journal of Glaciology*, v. 19, no. 81, p. 335-342.

Brown, C.B., Evans, R.J. and LaChapelle, E.R.
1972: Slab avalanching and the state of stress in fallen snow; *Journal of Geophysical Research*, v. 77, no. 24, p. 4570-4580.

Brown, C.B., Evans, R.J. *et al*
1973: *Incorporation of Glide and Creep Measurements in Snow Slab Mechanics*; U.S. Forest Service Rocky Mountain Forest and Range Experiment Station General Technical Report RM-3, Fort Collins, Colorado, p. 7-13.

Buser, O. and Frutiger, H.
1980: Observed maximum run-out distance of snow avalanches and the determination of the friction coefficients μ and ξ; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 121-130.

Campell, E.
1975: Snowdrift structures; in *Avalanche Protection in Switzerland*; U.S. Forest Service Rocky Mountain Forest and Range Experiment Station General Technical Report RM-9, Fort Collins, Colorado, p. 103-116.

Canadian Avalanche Committee
1981: *Guidelines for Weather, Snowpack and Avalanche Observations*; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 132, 48 p.

Cottman, B.
1966: A wet snow avalanche on a slope of 12 degrees; in *International Symposium on the Scientific Aspects of Snow and Ice Avalanches, 5-10 April 1965, Davos, Switzerland*; International Association of Scientific Hydrology Publ. no. 69, Gentbrugge, Belgium, p. 273-275.

Crécy, L. de
1980: Avalanche zoning in France - regulations and technical bases; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 325-330.

Dent, J.D. and Lang, T.E.
1980: Modeling of snow flow; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 131-140.

Dent, J.D. and Lang, T.E.
1982: Experiments on mechanics of flowing snow; *Cold Regions Science and Technology*, v. 5, no. 3, p. 253-258.

Eidg. Institut für Schnee-und Lawinenforschung
1979: *International Seminar on Mountain Forests and Avalanches, 25-28 September 1978, Davos, Switzerland*; Davos, 358 p.

Everts, K.
1976: *A progress report on the development of a remote control avalanche*

initiation system; Parks Canada, Department of Indian and Northern Affairs, Internal Report.

Everts, K. and Laidlaw, B.
1978: Research and development of avalanche control methods in Banff National Park; in *Avalanche Control, Forcasting (sic), and Safety, Proceedings of a Workshop Held in Banff, Alberta 1-4 November 1976*, ed. R. Perla; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 120, Ottawa, p. 30-41.

Ferguson, S.A.
1981: Interpreting snowpack structure (abstract); in *Proceedings of Avalanche Workshop, 3-5 November 1980, Vancouver, B.C.*, ed. Canadian Avalanche Committee; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 133, Ottawa, p. 62-64.

Föhn, P.M.B.
1979: Avalanche frequency and risk estimation in forest sites; in *International Seminar on Mountain Forests and Avalanches, September 25-28 1978, Davos, Switzerland*; Eidg. Institut für Schnee-und Lawinenforschung, Davos, p. 241-254.

Föhn, P.M.B.
1980: Snow transport over mountain crests; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 469-480.

Fraser, C.
1978: *Avalanches and Snow Safety*; John Murray, London, 269 p.

Freer, G.L. and Schaerer, P.A.
1980: Snow-avalanche hazard zoning in British Columbia, Canada; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 345-354.

Frutiger, H.
1970: Der Lawinenzonen Plan (LZP); in *Schweizerische Zeitschrift für Forstwesen*, 121 Jahrg., Nr. 4, p. 246-276.

Frutiger, H.
1977: Avalanche damage and avalanche protection in Switzerland; in *Glaciological Data-Avalanches (Report GD-1)*; World Data Center A: Glaciology, Institute for Arctic and Alpine Research, University of Colorado, Boulder, p. 17-32.

Frutiger, H.
1980: History and actual state of legalization of avalanche zoning in Switzerland; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 313-324.

Fukui, A.
1966: The classification of snow avalanches in Japan; in *International Symposium on the Scientific Aspects of Snow and Ice Avalanches, 5-10 April 1965, Davos, Switzerland*; International Association of Scientific Hydrology Publ. no. 69, Gentbrugge, Belgium, p. 377-381.

Gand, H.R. in der and Zupancic, M.
1966: Snow gliding and avalanches; in *International Symposium on the Scientific Aspects of Snow and Ice Avalanches, 5-10 April 1965, Davos, Switzerland*; International Association of Scientific Hydrology Publ. no. 69, Gentbrugge, Belgium, p. 230-242.

Gardner, J.S.
1983: Observations on erosion by wet snow avalanches, Mount Rae area, Alberta, Canada; *Arctic and Alpine Research*, v. 15, no. 2, p. 271-274.

Gardner, J.S., Smith, D.J. and Desloges, J.R.
1983: *The Dynamic Geomorphology of the Mt. Rae Area: A High Mountain Region in Southwestern Alberta*; Department of Geography Publication Series no. 19, University of Waterloo, Waterloo, 237 p.

Gardner, N.C. and Judson, A.
1970: *Artillery Control of Avalanches Along Mountain Highways*; U.S. Forest Service Rocky Mountain Forest and Range Experiment Station Research

Paper RM-61, Fort Collins, Colorado, 26 p.

Giddings, J.C. and LaChapelle, E.R.
1962: The formation rate of depth hoar; *Journal of Geophysical Research*, v. 67, no. 6, p. 2377-2382.

Golding, D.L.
1974: The correlation of snowpack with topography and snowmelt runoff on Marmot Creek Basin, Alberta; *Atmosphere*, v. 12, no. 1, p. 31-38.

Golding, D.L.
1977: Snowpack evaporation during chinooks along the East Slopes of the Rocky Mountains; in *Proceedings of the Second Conference on Hydrometeorology*; Atmospheric Environment Service, Toronto, p. 251-254.

Golding, D.L.
1978: Calculated snowpack evaporation during chinooks along the eastern slopes of the Rocky Mountains; *Journal of Applied Meteorology*, v. 17, p. 1647-1651.

Gubler, H.
1977: Artificial release of avalanches by explosives; *Journal of Glaciology*, v. 19, no. 81, p. 419-429.

Gunderson, E.
1978: *Kananaskis Avalanche Site Analysis - Phase 1. Smith-Dorrien Road and Secondary Road 940, Highwood Summit Section, December 1977 - February 1978*; Alberta Department of Highways and Transportation, Edmonton.

Hackett, S.W. and Santeford, H.S.
1980: Avalanche zoning in Alaska, U.S.A.; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 377-392.

Hawkes, B.C.
1979: *Fire History and Fuel Appraisal Study of Kananaskis Provincial Park, Alberta*; Resource Assessment and Management Section, Parks Division, Alberta Recreation and Parks, Edmonton.

Hestnes, E. and Lied, K.
1980: Natural-hazard maps for land-use planning in Norway; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 331-344.

Hettinger, L.R.
1975: *Vegetation of the Vine Creek Drainage Basin, Jasper National Park*; unpub. Ph.D. thesis, University of Alberta, Edmonton, 276 p.

Hobbs, P.V.
1965: The effect of time on the physical properties of deposited snow; *Journal of Glaciology*, v. 4, no. 35, p. 421-436.

Hutcheon, R. and Lie, L.
1978: Avalanche forecasting in Juneau, Alaska; in *Avalanche Control, Forcasting (sic), and Safety, Proceedings of a Workshop Held in Banff, Alberta, 1-4 November 1976*, ed. R. Perla; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 120, Ottawa, p. 101-115.

Israelson, C.
1978: An approach to ski area avalanche control; in *Avalanche Control, Forcasting (sic), and Safety, Proceedings of a Workshop Held in Banff, Alberta, 1-4 November 1976*, ed. R. Perla; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 120, Ottawa, p. 19-23.

Iversen, J.D.
1980: Drifting-snow similitude -- transport-rate and roughness modeling; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 393-404.

Ives, J.D. and Bovis, M.J.
1978: Natural hazards maps for land-use planning, San Juan Mountains, Colorado, U.S.A.; *Arctic and Alpine Research*, v. 10, no. 2, p. 185-212.

Ives, J.D. and Krebs, P.V.
1978: Natural hazards research and land-use planning responses in mountainous terrain: the town of Vail, Colorado Rocky Mountains, U.S.A.; *Arctic and Alpine Research*, v. 10, no. 2, p. 213-222.

Ives, J.D. and Plam, M.
1980: Avalanche hazard mapping and zoning problems in the Rocky Mountains, with examples from Colorado, U.S.A.; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 363-376.

Janz, B.
1968: Southern Alberta's paralyzing snowstorms in April 1967; *Weatherwise*, v. 21, p. 70-75.

Janz, B.
1976: Synoptic patterns associated with heavy spring snowfalls in southwestern Alberta; in *Proceedings of the 44th Annual Meeting of the Western Snow Conference, April 20-22 1976, Calgary*; p. 48-55.

Johnson, J.B.
1980: A model for snow-slab failure under conditions of dynamic loading; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 245-254.

Judson, A.
1964: Relative importance of weather factors creating slab avalanches in Colorado; in *Proceedings of the 32nd Annual Meeting of the Western Snow Conference, 21-23 April, Nelson, B.C.*, p. 60-67.

Judson, A.
1967: Snow cover and avalanches in the high alpine zone of western United States; in *Physics of Snow and Ice, Proceedings of the International Conference on Low Temperature Science, 14-19 August 1966, Sapporo, Japan*; v. 1, pt. 2, p. 1151-1160.

Judson, A. and Erickson, B.J.
1973: *Predicting Avalanche Intensity from Weather Data: A Statistical Analysis*; U.S. Forest Service Rocky Mountain Forest and Range Experiment Station Research Paper RM-112, Fort Collins, Colorado, 12 p.

Kahn, M.
1966a: *A study of snow avalanches and their environment by stereophotogrammetric and geophysical methods*; presented at the International Conference on Low Temperature Science, 14-19 August 1966, Sapporo, Japan; 15 p.

Kahn, M.
1966b: *Interpretation of stereophotogrammetric records of a snow avalanche, and some considerations on the avalanche flow*; presented at the International Conference on Low Temperature Science, 14-19 August 1966, Sapporo, Japan; 15 p.

Kahn, M.
1972: *Studying the Slide Pattern of Avalanches by Means of Photogrammetric Methods*; Cold Regions Research and Engineering Laboratory Translation 207; U.S. Army Material Command, Hanover, N.H., 12 p.

Keeler, C.M.
1969: The growth of bonds and the increase of mechanical strength in a dry seasonal snow-pack; *Journal of Glaciology*, v. 8, no. 54, p. 441-450.

Keeler, C.M. and Weeks, W.F.
1968: Investigations into the mechanical properties of alpine snow-packs; *Journal of Glaciology*, v. 7, no. 50, p. 253-271.

Kirby, C.L.
1973: *The Kananaskis Forest Experiment Station, Alberta*; Northern Forest Research Centre Information Report NOR-X-51; Environment Canada, Edmonton.

Kobayashi, F.
1978: The time-delay method of avalanche control; in *Avalanche Control, Forcasting (sic), and Safety, Proceedings of a Workshop Held in Banff, Alberta 1-4 November 1976*, ed. R. Perla; National Research Council of

Canada Associate Committee on Geotechnical Research Technical Memorandum no. 120, Ottawa, p. 50-55.

Kotlyakov, V.M. and Plam, M.Ya.
1966: The influence of drifting on snow distribution in the mountains and it's role in the formation of avalanches; in *International Symposium on the Scientific Aspects of Snow and Ice Avalanches, 5-10 April 1965, Davos, Switzerland*; International Association of Scientific Hydrology Publ. no. 69, Gentbrugge, Belgium, p. 53-60.

LaChapelle, E.R.
1966: Avalanche forecasting -- a modern synthesis; in *International Symposium on the Scientific Aspects of Snow and Ice Avalanches, 5-10 April 1965, Davos, Switzerland*; International Association of Scientific Hydrology Publ. no. 69, Gentbrugge, Belgium, p. 350-356.

LaChapelle, E.R.
1967: The relation of crystal riming to avalanche formation in new snow; in *Physics of Snow and Ice, Proceedings of the International Conference on Low Temperature Science, 14-19 August 1966, Sapporo, Japan*; v. 1, pt. 2, p. 1169-1176.

LaChapelle, E.R.
1969: *Field Guide to Snow Crystals*; J.J. Douglas, Vancouver, 101 p.

LaChapelle, E.R.
1970: Principles of avalanche forecasting; in *Ice Engineering and Avalanche Forecasting and Control, Proceedings of a Conference Held at the University of Calgary 23-24 October 1969*, comp. L.W. Gold and G.P. Williams; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 98, Ottawa, p. 106-113.

LaChapelle, E.R.
1974: Avalanche forecasting; in *Development of Methodology for Evaluation and Prediction of Avalanche Hazard in the San Juan Mountain area of Southwestern Colorado*, R.L. Armstrong, E.R. LaChapelle, M.J. Bovis and J.D. Ives; Institute of Arctic and Alpine Research Occasional Paper no. 13, University of Colorado, Boulder, p. 41-55.

LaChapelle, E.R.
1977a: Alternate methods for the artificial release of snow avalanches; *Journal of Glaciology*, v. 19, no. 81, p. 389-397.

LaChapelle, E.R.
1977b: Snow avalanches: a review of current research and applications; *Journal of Glaciology*, v. 19, no. 81, p. 313-323.

LaChapelle, E.R.
1978: New experiments with methods for avalanche release; in *Avalanche Control, Forcasting (sic), and Safety, Proceedings of a Workshop Held in Banff, Alberta 1-4 November 1976*, ed. R. Perla; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 120, Ottawa, p. 56-60.

LaChapelle, E.R.
1980: The fundamental processes in conventional avalanche forecasting; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 75-84.

LaChapelle, E.R. and Armstrong, R.L.
1976: Nature and causes of avalanches in the San Juan Mountains; in *Avalanche Release and Snow Characteristics, San Juan Mountains, Colorado*, ed. R.L. Armstrong and J.D. Ives; Institute of Arctic and Alpine Research Occasional Paper no. 19, University of Colorado, Boulder, p. 23-40.

LaChapelle, E.R., Ferguson, S.A., Marriott, R.T., Moore, M.B., Reanier, F.W., Sackett, E.M. and Taylor, P.L.
1978: *Central Avalanche Hazard Forecasting -- Summary of Scientific Investigations*; Department of Atmospheric Sciences, University of Washington, Seattle (Washington State Department of Highways Report 23.4), 203 p.

LaChapelle, E.R. and Leonard, R.
1971: *North Cascades Highway SR-20 Avalanche Atlas*; Department of

Atmospheric Sciences, University of Washington, Seattle, 177 p.

LaChapelle, E.R., Marriott, R.T., Moore, M.B., Reanier, F.W., Sackett, E.M. and Taylor, P.L.
1978: *Central Avalanche Hazard Forecasting -- Final Report*; Department of Atmospheric Sciences, University of Washington, Seattle (Washington State Department of Highways Olympia Research Project 23.3), 116 p.

LaChapelle, E.R. and Stillman, R.M.
1966: The control of snow metamorphism by chemical agents; in *International Symposium on the Scientific Aspects of Snow and Ice Avalanches, 5-10 April 1965, Davos, Switzerland*; International Association of Scientific Hydrology Publ. no. 69, Gentbrugge, Belgium, p. 261-266.

Lang, T.E. and Brown, R.L.
1973: On the mechanics of the hard slab avalanche; in *Advances in North American Avalanche Technology: 1972 Symposium*, comp. R.I. Perla; U.S. Forest Service Rocky Mountain Forest and Range Experiment Station General Technical Report RM-3, Fort Collins, Colorado, p. 24-28.

Lang, T.E: and Brown, R.L.
1980: *Numerical Simulation of Snow Avalanche Impact on Structures*; U.S. Forest Service Rocky Mountain Forest and Range Experiment Station Research Paper RM-216, Fort Collins, Colorado, 21 p.

Lang, T.E., Dawson, K.L. and Martinelli, M., Jr.
1979: *Numerical Simulation of Snow Avalanche Flows*; U.S. Forest Service Rocky Mountain Forest and Range Experiment Station Research Paper RM-205, Fort Collins, Colorado, 51 p.

Laycock, A.H.
1957a: *A Physiographic classification of soils for Land Use Planning in the Eastern Slopes of the Canadian Rockies*; unpub. Ph.D. thesis, University of Minnesota, Minneapolis, 453 p.

Laycock, A.H.
1957b: *Precipitation and streamflow in the Mountain and Foothill Regions of the Saskatchewan River Basin*; Prairie Provinces Water Board Report no. 6, Regina, 48 p.

Laycock, A.H.
1961: *Hydro-Meteorology in Watershed Management Planning on the Eastern Slopes of the Canadian Rockies*; unpub. paper, Canadian Association of Geographers Annual Meeting, Montréal.

Leaf, C.F. and Martinelli, M., Jr.
1977: *Avalanche Dynamics: Engineering Applications for Land Use Planning*; U.S. Forest Service Rocky Mountain Forest and Range Experiment Station Research Paper RM-183, Fort Collins, Colorado, 51 p.

Lee, Y.
1969: *An Analysis of the Relation of Precipitation to Topography in the Interprovincial Boundary Regions of Alberta and British Columbia*; unpub. M.Sc. thesis, University of Alberta, Edmonton.

Lester, P.F.
1974: Climatology, in the mountain environment and urban society; in *Kananaskis Pilot Study*; Environmental Studies Centre (Kananaskis), University of Calgary, p. 151-191.

Longley, R.W.
1967: The frequency of winter chinooks in Alberta; *Atmosphere*, v. 5, no. 4, p. 4-16.

Longley, R.W.
1972: *The Climate of the Prairie Provinces*; Atmospheric Environment Service, Climatological Studies no. 13, Environment Canada, Ottawa, 79 p.

Lossev, K.S.
1966: Genetic classification of avalanches; in *International Symposium on the Scientific Aspects of Snow and Ice Avalanches, 5-10 April 1965, Davos, Switzerland*; International Association of Scientific Hydrology Publ. no. 69, Gentbrugge, Belgium, p. 394-396.

Louie, P.Y.T.
1977: Potential evaporative loss from snow in southwestern Alberta; in *Canadian Hydrology Symposium, 1977 Proceedings*; National Research Council of Canada, Ottawa, p. 24-32.

Maeno, N., Nishimura, K. and Kaneda, Y.
1980: Viscosity and heat transfer in fluidized snow; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 263-274.

Marbouty, D.
1980: An experimental study of temperature-gradient metamorphism; in Symposium on Snow in Motion, Colorado, 12-17 August 1979: *Journal of Glaciology*, v. 26, no. 94, p. 303-312.

Martinelli, M., Jr.
1971: *Physical Properties of Alpine Snow as Related to Weather and Avalanche Conditions*; U.S. Forest Service Rocky Mountain Forest and Range Experiment Station Research Paper RM-64, Fort Collins, Colorado, 35 p.

Martinelli, M., Jr.
1972: *Simulated Sonic Boom as an Avalanche Trigger*; U.S. Forest Service Rocky Mountain Forest and Range Experiment Station Research Note RM-224, Fort Collins, Colorado, 7 p.

Martinelli, M., Jr.
1974: *Snow Avalanche Sites - Their Identification and Evaluation*; U.S. Forest Service Rocky Mountain Forest and Range Experiment Station Agricultural Information Bulletin 360, Fort Collins, Colorado, 26 p.

McClung, D.M.
1975: Creep and the snow-earth interface condition in the seasonal alpine snowpack; in *Snow Mechanics, Proceedings of the Grindelwald Symposium, April 1974*; International Association of Scientific Hydrology Publ. no. 114, p. 235-248.

McClung, D.M.
1977: Direct simple shear tests on snow and their relation to slab avalanche formation; *Journal of Glaciology*, v. 19, no. 81, p. 101-109.

McClung, D.M.
1980: *Creep and Glide Processes in Mountain Snowpacks*; National Hydrology Research Institute Paper no. 6, Ottawa, 66 p.

McClung, D.M.
1981a: Fracture mechanical models of dry slab avalanche release; *Journal of Geophysical Research*, v. 86, no. B11, p. 10783-10790.

McClung, D.M.
1981b: A physical theory of snow gliding; *Canadian Geotechnical Journal*, v. 18, no. 1, p. 86-94.

McClung, D.M. and Schaerer, P.A.
1981: Snow avalanche size classification; in *Proceedings of Avalanche Workshop, 3-5 November 1980, Vancouver, B.C.*, ed. Canadian Avalanche Committee; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 133, Ottawa, p. 12-30.

McNair, D. and Wolfe, F., Jr.
1977: *An accoustic emissions monitoring system for avalanche snowpacks*; U.S. Forest Service Rocky Mountain Forest and Range Experiment Station Research Note RM-340, Fort Collins, Colorado, 4 p.

McPherson, H.J., Gardner, J.S., Steel, J., de Scally, F., McFarlane, R. and Smith, D.
1983: *Avalanche Hazard in Kananaskis Country, Alberta*; Alberta Environmental Research Trust, Government of Alberta, Internal Report, 143 p.

Mears, A.I.
1975: Dynamics of dense-snow avalanches interpreted from broken trees; *Geology*, v. 3, no. 9, p. 521-523.

Mears, A.I.
1980a: A fragment-flow model of dry-snow avalanches; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 153-164.

Mears, A.I.
1980b: Municipal avalanche zoning: contrasting policies of four western United States communities; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 355-362.

Mellor, M.
1965: *Blowing Snow*; Cold Regions Research and Engineering Laboratory Monograph, Part III, Section A3c; U.S. Army Material Command, Hanover, N.H., 79 p.

Mellor, M.
1968: *Avalanches*; Cold Regions Science and Engineering Laboratory Monograph, Part III, Section A3d; U.S. Army Material Command, Hanover, N.H., 215 p.

Mellor, M.
1973: Controlled release of avalanches by explosives; in *Advances in North American Avalanche Technology: 1972 Symposium*, comp. R.I. Perla; U.S. Forest Service Rocky Mountain Forest and Range Experiment Station General Technical Report RM-3, Fort Collins, Colorado, p. 37-50.

Mellor, M.
1974: *A Review of Basic Snow Mechanics*; U.S. Army Corps of Engineers Internal Report no. 352, Cold Regions Research and Engineering Laboratory, Hanover, N.H., 42 p.

Mellor, M. and Smith, J.H.
1966: Strength studies of snow; in *International Symposium on the Scientific Aspects of Snow and Ice Avalanches, 5-10 April 1965, Davos, Switzerland*; International Association of Scientific Hydrology Publ. no. 69, Gentbrugge, Belgium, p. 100-113.

Montagne, J., McPartland, J.T., Super, A.B. and Townes, H.W.
1968: *The Nature and Control of Cornices on the Bridger Range, Southwestern Montana*; U.S. Forest Service Alta Avalanche Study Center Miscellaneous Report no. 14, 23 p.

Moskalew, Ju.D.
1966: On the formation mechanism of wet snow avalanches; in *International Symposium on the Scientific Aspects of Snow and Ice Avalanches, 5-10 April 1965, Davos, Switzerland*; International Association of Scientific Hydrology Publ. no. 69, Gentbrugge, Belgium, p. 196-198.

Narita, H.
1980: Mechanical behaviour and structure of snow under uniaxial tensile stress in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 275-282.

Nkemdirm, L.C. and Weber, L.
1976: Wet and dry sequences in precipitation regimes; *Geographiska Annaler*, v. 58A, no. 4, p. 303-314.

Norem, H.
1978: Use of snow fences to reduce avalanche hazards; in *Avalanche Control, Forcasting (sic), and Safety, Proceedings of a Workshop Held in Banff, Alberta, 1-4 November 1976*, ed. R. Perla; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 120, Ottawa, p. 67-72.

Obled, C.
1970: *Vers une prévision numérique des risques d'avalanches*; Comité d'Études et de Documentation Nivologiques et Glaciaires, Contract Report D.G.R.S.T. 69/02/094, Grenoble.

Ogilvie, R.T.
1969: The mountain forest and alpine zones of Alberta; in *Vegetation, Soils and Wildfire*, ed. J.G. Nelson and M.J. Chambers; Methuen Publications, Toronto, p. 25-44.

Oppliger, H.
1975: Avalanche protective measures; in *Avalanche Protection in Switzerland*; U.S. Forest Service Rocky Mountain Forest and Range Experiment Station General Technical Report RM-9, Fort Collins, Colorado, p. 19-37.

Oura, H.
1967: Studies on blowing snow I; in *Physics of Snow and Ice, Proceedings of the International Conference on Low Temperature Science, 14-19 August 1966, Sapporo, Japan*; v. 1, pt. 2, p. 1085-1097.

Oura, H., Ishida, T., Kobayashi, D., Kobayashi, S. and Yamada, T.
1967: Studies on blowing snow II; in *Physics of Snow and Ice, Proceedings of*

the International Conference on Low Temperature Science, 14-19 August 1966, Sapporo, Japan; v. 1, pt. 2, p. 1099-1118.

Palm, E. and Tveitereid, M.
1979: On heat and mass flux through dry snow; *Journal of Geophysical Research*, V. 84, no. C2, p. 745-749.

Perla, R.I.
1969: Strength tests on newly fallen snow; *Journal of Glaciology*, v. 8, no. 54, p. 427-440.

Perla, R.I.
1970: On contributory factors in avalanche hazard evaluation; Canadian Geotechnical Journal, v. 7, p. 414-419.

Perla, R.I.
1977: Slab avalanche measurements; *Canadian Geotechnical Journal*, v. 14, no. 2, p. 206-213.

Perla, R.I.
1978: Artificial release of avalanches in North America; *Arctic and Alpine Research*, v. 10, no. 2, p. 235-240.

Perla, R.I., Beck, T.M.H. and Cheng, T.T.
1982: The shear strength index of alpine snow; *Cold Regions Science and Technology*, v. 6, no. 1, p. 11-20.

Perla, R.I., Cheng, T.T. and McClung, D.M.
1980: A two-parameter model of snow-avalanche motion; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 197-208.

Perla, R.I. and LaChapelle, E.R.
1970: A theory of snow slab failure; *Journal of Geophysical Research*, v. 75, no. 36, p. 7619-7627.

Perla, R.I. and Martinelli, M., Jr.
1976: *Avalanche Handbook*; U.S. Forest Service Rocky Mountain Forest and Range Experiment Station Agriculture Handbook no. 489, Fort Collins, Colorado, 254 p.

Plesnik, P.
1973: Some patterns of the timberline in the Rocky Mountains compared with Central Europe; *Arctic and Alpine Research*, v. 5, no. 3, pt. 2, p. A77-A84.

Potter, N., Jr.
1969: Tree ring dating of snow avalanche tracks and the geomorphic activity of avalanches, Northern Absoroka Mountains, Wyoming; in *U.S. Contributions to Quaternary Research*, ed. S.A. Schumm and W.C. Bradley; Geological Society of America Special Paper no. 123, p. 141-165.

Powell, J.M.
1973: *Climate in the Kananaskis Forest Experiment Station* (ed. C.L. Kirby); Northern Forest Research Center Information Report NOR-X-51, Canadian Forestry Service, Environment Canada, Edmonton, 50 p.

Powell, J.M.
1977: Precipitation climatology of the eastern slopes area of Alberta; in *Alberta Watershed Research Program Symposium Proceedings 1977*, ed. R.H. Swanson and P.A. Logan; Northern Forest Research Center, Canadian Forestry Service, Environment Canada, Edmonton, p. 188-204.

Price, L.W.
1981: *Mountains and Man*; University of California Press, Berkeley, 506 p.

Quervain, M.R. de
1958: Avalanche classification; in *Proceedings - International Association of Scientific Hydrology / International Union of Geodesy and Geophysics General Assembly, Toronto, 1957*; International Association of Scientific Hydrology Publ. no. 46, v. 4, p. 387-392.

Quervain, M.R. de
1963: On the metamorphism of snow; in *Ice and Snow*, ed. W.D. Kingery; Massachusetts Institute of Technology Press, Cambridge, p. 377-390.

Quervain, M.R. de
1975: Avalanche formation; in *Avalanche Protection in Switzerland*; U.S.

Forest Service Rocky Mountain Forest and Range Experiment Station General Technical Report RM-9, Fort Collins, Colorado, p. 6-18.

Quervain, M.R. de
1979: Wald und Lawinen (abstract); in *International Seminar on Mountain Forests and Avalanches, 25-28 September 1978, Davos, Switzerland*; Eidg. Institut für Schnee-und Lawinenforschung, Davos, p. 219-220.

Quervain, M.R. de, Crécy, L. de, LaChapelle, E.R., Lossev, K. and Shoda, M.
1973: Proposal of the working group on avalanche classification of the International Commission on Snow and Ice; *Hydrological Sciences Bulletin*, v. 18, no. 4, p. 391-402.

Ramseier, R.O. and Sander, G.W.
1966: Sintering of snow as a function of temperature; in *International Symposium on the Scientific Aspects of Snow and Ice Avalanches, 5-10 April 1965, Davos, Switzerland*; International Association of Scientific Hydrology Publ. no. 69, Gentbrugge, Belgium, p. 119-127.

Reinelt, E.R.
1970: On the role of orography in the precipitation regime in Alberta; *The Albertan Geographer*, v. 6, p. 45-58.

Rheumer, G.A.
1953: *Climate and Climatic Regions of Western Canada*; unpub. Ph.D. thesis, University of Illinois, Urbana, 185 p.

Roch, A.
1966: Les variations de la résistance de la neige; in *International Symposium on the Scientific Aspects of Snow and Ice Avalanches, 5-10 April 1965, Davos, Switzerland*; International Association of Scientific Hydrology Publ. no. 69, Gentbrugge, Belgium, p. 86-99.

Roch, A.
1981: The starting mechanism of avalanches; in *Proceedings of Avalanche Workshop, 3-5 November 1980, Vancouver, B.C.*, ed. Canadian Avalanche Committee; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 133, Ottawa, p. 1-8.

Salm, B.
1966: Contribution to avalanche dynamics; in *International Symposium in the Scientific Aspects of Snow and Ice Avalanches, 5-10 April 1965, Davos, Switzerland*; International Association of Scientific Hydrology Publ. no. 69, Gentbrugge, Belgium, p. 199-214.

Salm, B.
1968: On nonuniform, steady flow of avalanching snow; in *Union de Géodésie et Géophysique Internationale. Association Internationale d'Hydrologie Scientifique. Assemblée générale de Berne, 25 sept.7 oct. 1967. [Commission de Neiges et Glaces]. Rapports et discussions*; International Association of Scientific Hydrology Publ. no. 79, p. 19-29.

Salway, A.A.
1978: A seismic and transducer system for monitoring velocities and impact pressures of snow avalanches; *Arctic and Alpine Research*, v. 10, no. 4, p. 769-774.

Santeford, H.S., Jr.
1972: *Management of Windblown Alpine Snows*; unpub. Ph.D. thesis, Colorado State University, Fort Collins.

Schaerer, P.
1962: *The Avalanche Hazard Evaluation and Prediction at Rogers Pass*; National Research Council of Canada Division of Building Research Technical Paper no. 142, Ottawa, 68 p.

Schaerer, P.
1967: The amount of snow deposited at avalanche sites; in *Physics of Snow and Ice, Proceedings of the International Conference on Low Temperature Science, 14-19 August 1966, Sapporo, Japan*; v. 1, pt. 2, p. 1255-1260.

Schaerer, P.
1973: Observations of avalanche impact pressures; in *Advances in North American Avalanche Technology: 1972 Symposium*, comp. R.I. Perla; U.S. Forest Service Rocky Mountain Forest and Range Experiment Station General Technical Report RM-3, Fort Collins, Colorado, p. 51-54.

Schaerer, P.
1975: Friction coefficients and speed of flowing avalanches; in *[Union Geodesique et Geophysique Internationale. Association Internationale des Sciences Hydrologiques. Commission des Neiges et Glaces] Symposium. Mecanique de la neige. Actes du colloque de Grindelwald, avril 1974*; International Association of Scientific Hydrology Publ. no. 114, p. 425-432.

Schaerer, P. and Salway, A.A.
1980: Seismic and impact-pressure monitoring of flowing avalanches; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 179-188.

Schmidt, R.A.
1980: Threshold wind-speeds and elastic impact in snow transport; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 453-468.

Seligman, G.
1936: *Snow Structure and Ski Fields*; MacMillan and Co., London, 555 p.

Shimizu, H.
1967: Magnitude of avalanches; in *Physics of Snow and Ice, Proceedings of the International Conference on Low Temperature Science, 14-19 August 1966, Sapporo, Japan*; v. 1, pt. 2, p. 1269-1276.

Shoda, M.
1967: Aerial observation and thin section studies on avalanches; in *Physics of Snow and Ice, Proceedings of the International Conference on Low Temperature Science, 14-19 August 1966, Sapporo, Japan*; v. 1, pt. 2, p. 1137-1150.

Simms, J.
1978: Avalanche forecasting at Jackson Hole ski area; in *Avalanche Control, Forcasting (sic), and Safety, Proceedings of a Workshop Held in Banff, Alberta, 1-4 November 1976*, ed. R. Perla; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 120, Ottawa, p. 77-86.

Smith, L.
1973: Indication of snow avalanche periodicity through interpretation of vegetation patterns in the North Cascades, Washington; in *Methods of Avalanche Control on Washington Mountain Highways*, C.R. Brown, R.J. Evans, P. Fox, E. LaChapelle, D.M. McClung and L. Smith; Washington State Department of Highways Research Program Report 8.4, p. 55-102.

Smith, D.J.
1979: *Periglacial Morphology and Environments of the Mt. Rae Area, Southwestern Alberta*; unpub. M.A. thesis, University of Waterloo, Waterloo, 320 p.

Sneyd, A.R.
1982: *Watershed Management in the Kananaskis District, East Slopes, Alberta*; unpub. M.Sc. thesis, University of Alberta, Edmonton, 389 p.

Sommerfeld, R.A.
1969: The role of stress concentration in slab avalanche release; *Journal of Glaciology*, v. 8, no. 54, p. 451-462.

Sommerfeld, R.A. and LaChapelle, E.
1970: The classification of snow metamorphism; *Journal of Glaciology*, v. 9, no. 55, p. 3-17.

Steel, J.M.
1982: *The Frequency and Magnitude of Avalanche Activity of Three Alpine Slopes in the Highwood Pass/Elbow Lake Region of Southwestern Alberta*; unpub. B.E.S. thesis, University of Waterloo, Waterloo, 167 p.

Stethem and Associates Ltd.
1983: *Avalanche Atlas: Smith-Dorrien Spray Lakes Road*; Report prepared for Alberta Transportation, 40 p.

Stethem, C. and Hetherington, J.
1978: Whistler Mountain avalanche control programme; in *Avalanche Control, Forcasting (sic), and Safety, Proceedings of a Workshop Held in Banff, Alberta, 1-4 November 1976*, ed. R. Perla; National Research Council of

Canada Associate Committee on Geotechnical Research Technical Memorandum no. 120, Ottawa, p. 24-29.

Stethem, C. and Perla, R.
1980: Snow-slab studies at Whistler Mountain, British Columbia, Canada; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 85-92.

Stethem, C. and Tweedy, J.W.
1981: Field tests of snow stability; in *Proceedings of Avalanche Workshop, 3-5 November 1980, Vancouver, B.C.*, ed. Canadian Avalanche Committee; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 133, Ottawa, p. 52-61.

St. Lawrence, W.F.
1980: The acoustic emission response of snow; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 209-216.

Storr, D.
1967: Precipitation variations in a small forested watershed; in *Proceedings of the 35th Annual Meeting of the Western Snow Conference, 18-20 April, Boise*, p. 11-17.

Storr, D.
1973: Wind-snow relations at Marmot Creek, Alberta; *Canadian Journal of Forest Research*, v. 3, no. 4, p. 479-485.

Storr, D. and Golding, D.L.
1976: Comparison of precipitation gauge and snowpillow data from a severe April snowstorm in a mountain watershed; in *Proceedings of the 44th Annual Meeting of the Western Snow Conference, 20-22 April, Calgary*, p. 78-86.

Tabler, R.D.
1975: Predicting profiles of snowdrifts in topographic catchments; in *Proceedings on the 43rd Annual Meeting of the Western Snow Conference, 23-25 April, Coronado, California*, p. 87-97.

Tabler, R.D.
1980a: Geometry and density of drifts formed by snow fences; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 405-420.

Tabler, R.D.
1980b: Self-similarity of wind profiles in blowing snow allows outdoor modelling; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 421-434.

Takeuchi, M.
1980: Vertical profile and horizontal increase of snow-drift transport; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 481-492.

Tarquin, P.
1977: *Sediment Transport in Snow Avalanches and the Related Geomorphic Features in the Highwood Pass/Elbow Lake Area, Southern Alberta*; unpub. M.A. thesis, University of Waterloo, Waterloo, 147 p.

Tesche, T.W. and Yocke, M.A.
1978: Application of numerical wind models to snow avalanche forecasting: overview; in *Avalanche Control, Forcasting (sic), and Safety, Proceedings of a Workshop Held in Banff, Alberta, 1-4 November 1976*, ed. R. Perla; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 120, Ottawa, p. 161-176.

Trottier, G.C.
1972: *Ecology of the Alpine Vegetation of Highwood Pass, Alberta*; unpub. M.Sc. thesis, University of Calgary, Calgary, 229 p.

U.S. Forest Service
1953: *Avalanche Handbook*; U.S. Department of Agriculture, Washington, D.C.

Voellmy, A.
1955: Über die Zerstörungskraft von Lawinen; *Schweizerische Bauzeitung*,

Jahrg. 73, p. 159-165, 212-217, 246-249, 280285 [English translation: On the destructive force of avalanches; U.S. Forest Service Alta Avalanche Study Center Translation no. 2, 1964].

Watanabe, Z.
1980: Tensile strain and fracture of snow; in Symposium on Snow in Motion, Colorado, 12-17 August 1979; *Journal of Glaciology*, v. 26, no. 94, p. 255-262.

Wheeler, J.O., Campbell, R.B., Reesor, J.E. and Mountjoy, E.W.
1972: *Structural Style of the Southern Canadian Cordillera*; Guidebook, Field Excursion X01-A01 of the 24th International Geological Congress, Montreal.

Wijk, M.C. van
1967: Photogrammetry applied to avalanche studies; *Journal of Glaciology*, v. 6, no. 48, p. 917-933.

Williams, K.
1978: The Colorado avalanche warming programme; in *Avalanche Control, Forcasting (sic), and Safety, Proceedings of a Workshop Held in Banff, Alberta, 1-4 November 1976*, ed. R. Perla; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 120, Ottawa, p. 116-131.

Williams, K.
1981: Weather and avalanche forecasting: where do we stand?; in *Proceedings of Avalanche Workshop 3-5 November 1980, Vancouver, B.C., ed. Canadian Avalanche Committee*; National Research Council of Canada Associate Committee on Geotechnical Research Technical Memorandum no. 133, Ottawa, p. 31-41.

Yosida, Z.
1963: Physical properties of snow; in *Ice and Snow - Properties, Processes and Applications*, ed. W.D. Kingery; Massachusetts Institute of Technology Press, Cambridge, p. 485-527.

Zingg, Th.
1966: Relation between weather situation, snow metamorphism and avalanche activity; in *International Symposium on the Scientific Aspects of Snow and Ice Avalanches, 5-10 April 1965, Davos, Switzerland*; International Association of Scientific Hydrology Publ. no. 69, Gentbrugge, Belgium, p. 61-64.

APPENDIX 1: FORMAT FOR WEATHER, SNOWPACK AND AVALANCHE OBSERVATIONS

APPENDIX 1 FORMAT FOR WEATHER, SNOWPACK AND AVALANCHE OBSERVATIONS

Source: Canadian Avalanche Committee (1981)

1. WEATHER OBSERVATIONS

a. Sky condition

class	symbol	description
Clear	○	No clouds
Scattered Cloud	◐	Sky is half or less covered with clouds.
Broken Cloud	◍	More than half but not all of the sky is covered with clouds.
Overcast	⊕	Sky is completely covered.
Obscured	⊗	Cloud elements are not discernible; for example the observer is in fog, smoke or haze.

b. Precipitation

class	symbol	description
No Precipitation	NIL	
Very Light Snow	VL*	Occasional snowflake
Light Snow	L*	Continuous snow that accumulates at a rate of 1cm per hour or less.
Moderate Snow	M*	Snow accumulates at a rate of 1cm to 3cm per hour.
Heavy Snow	H*	Snow accumulates at a rate of more than 3cm per hour.
Very Light Rain	VLR	Occasional raindrop
Light Rain	LR	Accumulation of 3mm of water per hour or less.

class	symbol	description
Moderate Rain	MR	Accumulation of 3mm to 8mm of water per hour.
Heavy Rain	HR	Accumulation of 8mm of water per hour or more.

c. Wind

Direction from which wind blows is recorded to eight points of the compass: N, NE, E, SE, S, SW, W, NW.

class	speed ($m\ s^{-1}$)	description
Calm	0	No air motion
Light	0-7	Light to gentle breeze; flags and twigs in motion.
Moderate	8-11	Fresh breeze; small trees sway and snow begins to drift.
Strong	11	Strong breeze and gale; whole trees in motion and snow drifting.

2. SNOWPACK OBSERVATIONS

a. Layer hardness (R)

Determined by the object that can be pushed into the snow in a horizontal direction with moderate effort (5 kg).

class	symbol	description
Very Soft	VS	Fist in glove
Soft	S	Four fingers in glove
Moderate Hardness	M	One finger in glove
Hard	H	Pencil
Very Hard	VH	Knife
Ice Layer		

b. Grain-type symbols (F)

unmetamorphosed new snow

+	new snow
+r	new snow, rimed
⋇	graupel
V	surface hoar

equi-temperature metamorphism

⌒	early stage (partially settled snow)
●	late stage (rounded grains)

temperature gradient metamorphism

□	early stage depth hoar (crystals with facets)
Λ	late stage depth hoar (partially or fully developed cups)

melt-freeze metamorphism

o	rounded grains clearly the result of melt-freeze cycling
C	clustered grains

c. Grain size (D)

Provided as diameter in mm; eg. 1-1.5mm

d. Free water content (W)

class	symbol	description
Dry	D	The snow crumbles when squeezed.
Moist	M	The snow sticks together and a snowball forms when squeezed. Water is not visible even with the aid of a magnifying glass.
Wet	W	Water can be recognized between adjacent snow grains, but cannot be pressed out when squeezed.
Very Wet	VW	Water can be pressed out by moderately squeezing.

class	symbol	desription
Slush	S	The snow is flooded; water runs out when a sample is picked up.

e. Snow density

G= Specific Gravity (G of water is 1.0)

f. Shovel shear test

class	desription
Very Easy	Fails during cutting or insertion of shovel.
Easy	Fails with minimum pressure.
Moderate	Fails with moderate pressure.
Hard	Fails with firm sustained pressure.

3. AVALANCHE OBSERVATIONS

Avalanche size classification

size	typical mass*	description
1	10t	Slough; too small to injure a person.
2	10^2t	The avalanche could injure or bury a person.
3	10^3t	The avalanche could bury and destroy a car, damage a truck, destroy a small building, or break a few trees.
4	10^4t	The avalanche could destroy a railway locomotive, large truck, several buildings, or a forest with an area up to 4ha (about 10 acres).
5	10^5t	The avalanche could destroy a village or a forest with an area of 40ha (about 100 acres).

*McClung and Schaerer (1981)

SAMPLE OF FIELD WEATHER OBSERVATIONS, WINTER 1982-83*

Fortress Mountain 2100 m elevation Area of sampling tube: 26.0 cm^2

DATE	16/12	9/1	23/1	5/2	23/2	10/3	25/3	10/4	18/4	3/5	18/5
TIME	1530	1410	1135	1225	1200	1530	1630	1400	1830	1800	1015
SKY	⊕	⊕	⊕	○	◐	⊕	◐	⊕	○	◐	⊕
WEATHER	L*	L*	M*	NIL	NIL	M*	NIL	L*	NIL	NIL	M*
MAX. TEMP. °C	+2.0	+2.2	+4.4	+3.3	+7.2	+10.0	+5.5	+11.1	+13.3	+14.4	+11.1
MIN. TEMP. °C	-23.0	-18.3	-17.2	-21.7	-18.9	-12.2	-20.0	-12.2	-15.0	-8.8	-6.1
PRES. TEMP. °C	0.0	-5.5	-15.0	-9.5	+3.3	+3.3	+1.6	-1.7	+5.0	+6.6	-1.1
THERMOGRAPH °C	-3.0	-5.5	-12.0	-9.5	+2.0	+2.0	+1.5	-1.0	+3.0	+6.0	0.0
REL. HUMID. %	+	+	+	+	+	+	+	+	+	+	+
NEW SNOW cm	20	19	35	11	Trace	11	11	13	-	15	1
STORM cm	+	+	+	+	+	+	+	+	+	+	+
INTERVAL cm	+	+	+	+	+	+	+	+	+	+	+
SNOWPACK cm	47	65	95	82	78	98	100	117	100	87	80
WEIGHT NEW g	82	61	87	36	-	70	63	60	-	130	-
WATER EQUIV.mm	32	23	33	14	-	27	24	23	-	50	-
SPEC. GRAV.	.16	.12	.09	.13	-	.25	.22	.18	-	.33	.10
PRECIP. GAUGE mm	+	+	+	+	+	+	+	+	+	+	+
FOOT PENETR.cm	36	30	65	75	82	80	30	57	20	+	2
WIND: BASE	SE; l-m	S; m	NW; l	CALM	E; l	NE; m	CALM	SE; l	CALM	NW; l	W; l
WIND: HIGH	SE; m-s	S; s	+	CALM	E; m	SE; m-s	CALM	S-SE; m	CALM	W; m	W; m
SNOWPACK: AVALANCHE PATH cm	+	65	107	97	95	90	105	110	95	80	+

*after Canadian Avalanche Committee (1981)

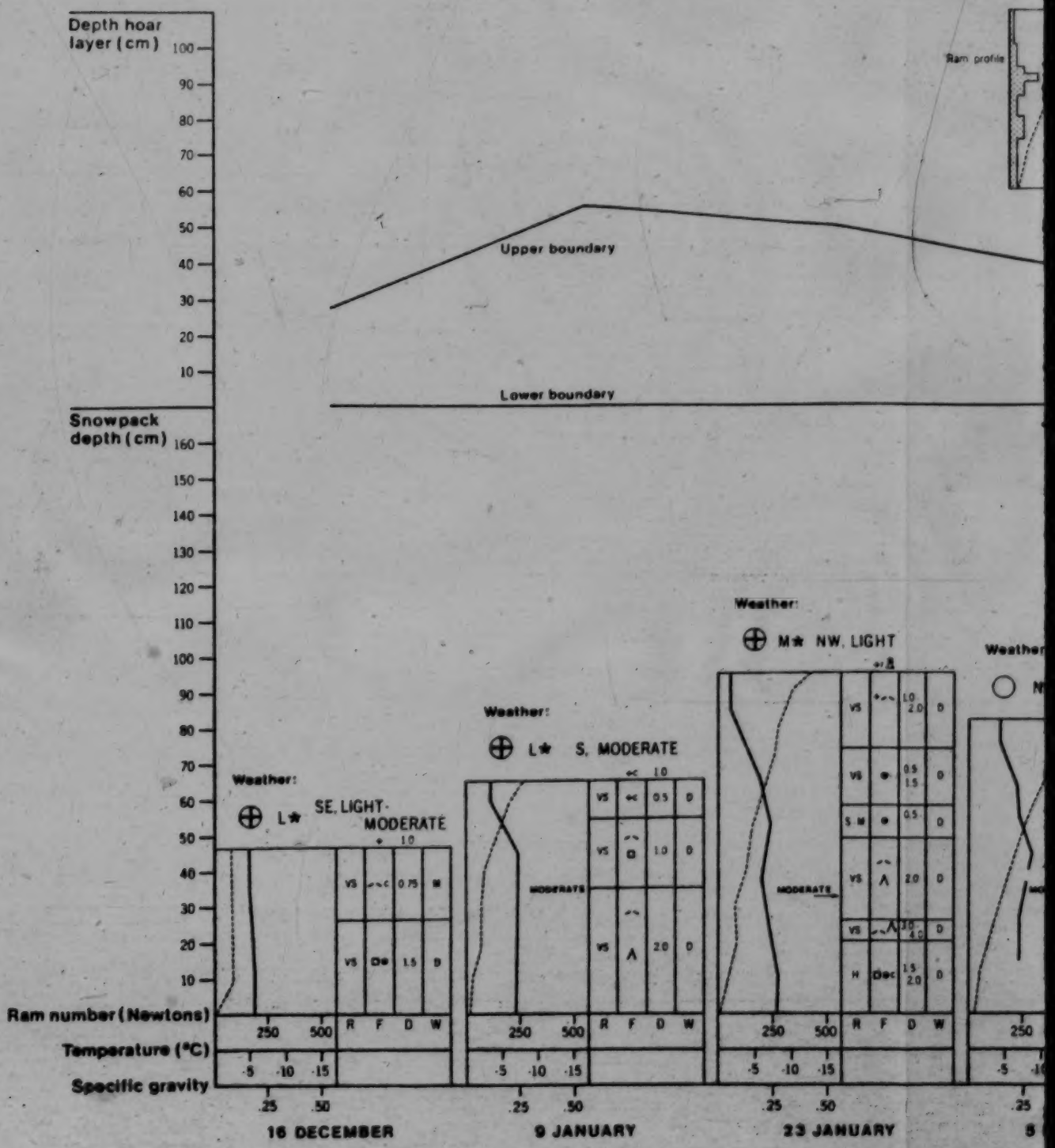
+not recorded

APPENDIX 2: TIME PROFILES; FORTRESS MOUNTAIN AND HIGHWOOD PASS, 1982-83

1 of F

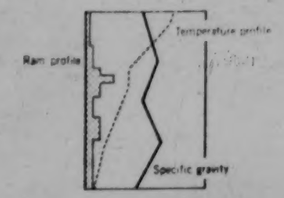
FORTRESS MOUNTAIN TIME PROFILE, 1982 -

2100 metres ASPECT: Northeast SLOPE INCLINE: Level



E PROFILE, 1982-83

SLOPE INCLINE: Level



SNOWPACK OBSERVATIONS

Layer hardness (R)
- VS Very soft
- S Soft
- M Moderate hardness
- H Hard
- VH Very hard
- ice layer

Grain type (F)
unmetamorphosed new snow
- + New snow
- +· New snow - rimed
- Graupel
- V Surface hoar

equi-temperature metamorphism
- Early stage
- ● Late stage

temperature gradient metamorphism
- □ Early stage depth hoar
- ∧ Late stage depth hoar

melt-freeze metamorphism
- ○ Rounded grains clearly the result of melt-freeze cycling
- c Clustered grains

Grain size (D) in millimetres

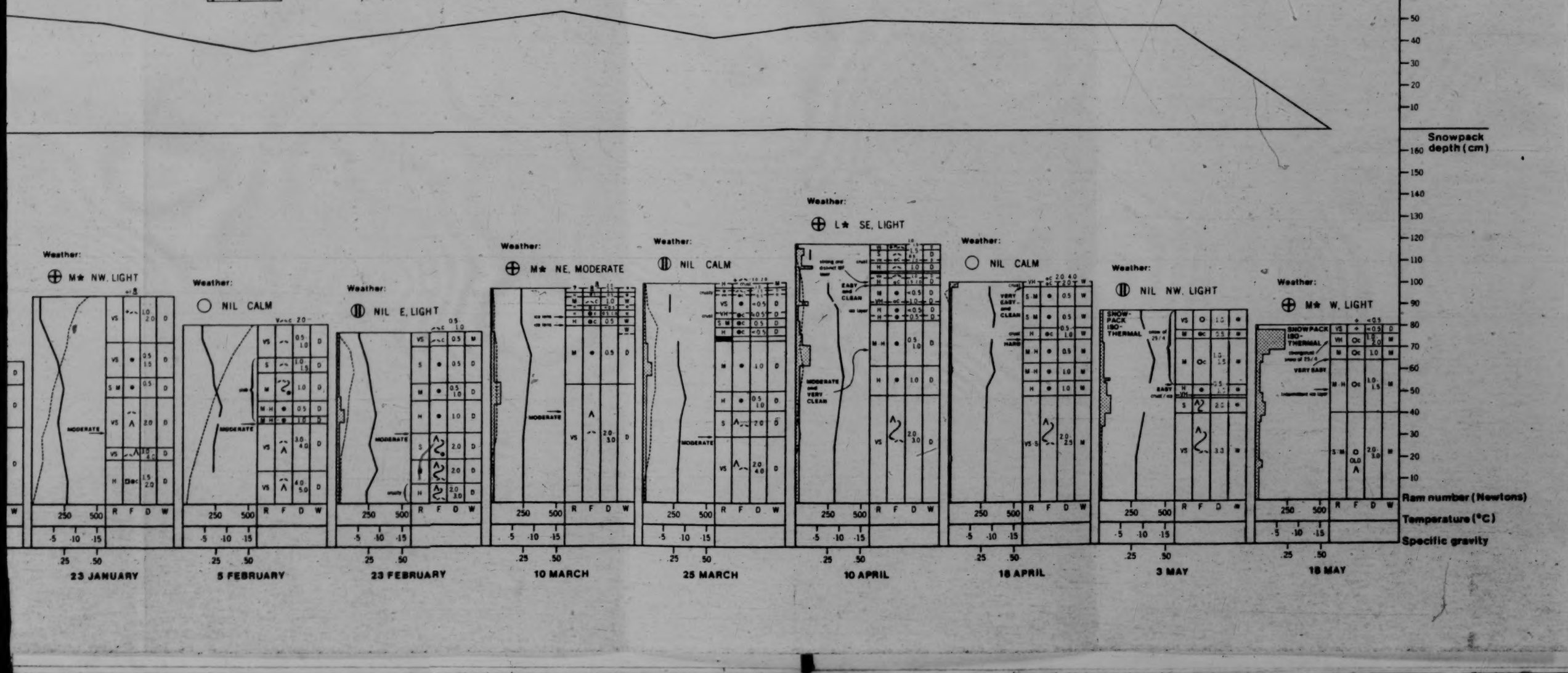
Free water content (W)
- D Dry
- M Moist
- W Wet
- VW Very wet

WEATHER OBSERVATIONS

Sky conditions
- Clear
- Scattered cloud
- Broken cloud
- Overcast
- Obscured

Precipitation
- NIL No precipitation
- VL★ Very light snow
- L★ Light snow
- M★ Moderate snow
- H★ Heavy snow

Wind
- CALM 0 m s⁻¹
- LIGHT 0-7 m s⁻¹
- MODERATE 8-11 m s⁻¹
- STRONG >11 m s⁻¹


Depth hoar layer (cm)
Snowpack depth (cm)
Ram number (Newtons)
Temperature (°C)
Specific gravity
Weather: ⊕ M★ NW, LIGHT — 23 JANUARY
Weather: ○ NIL CALM — 5 FEBRUARY
Weather: ◐ NIL E, LIGHT — 23 FEBRUARY
Weather: ⊕ M★ NE, MODERATE — 10 MARCH
Weather: ◐ NIL CALM — 25 MARCH
Weather: ⊕ L★ SE, LIGHT — 10 APRIL
Weather: ○ NIL CALM — 18 APRIL
Weather: ◐ NIL NW, LIGHT — 3 MAY
Weather: ⊕ M★ W, LIGHT — 18 MAY

1 of F

HIGHWOOD PASS TIME PROFILE, 1982-83

2208 metres ASPECT: – SLOPE INCLINE: Level

Depth hoar layer (cm) 100 90 80 70 60 50 40 30 20 10

Snowpack depth (cm) 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10

Ram number (Newtons)

Temperature (°C)

Specific gravity

SNOWPACK OBSERVATIONS

Layer hardness (R)
- VS Very soft
- S Soft
- M Moderate hardness
- H Hard
- VH Very hard
- Ice layer

Grain type (F)
unmetamorphosed new snow
- + New snow
- +r New snow-rimed
- Graupel
- V Surface hoar

equi-temperature metamorphism
- Early stage
- Late stage

temperature gradient metamorphism
- Early stage depth hoar
- Late stage depth hoar

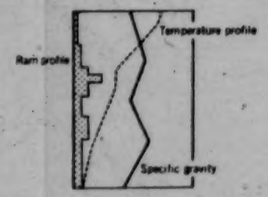
melt-freeze metamorphism
- O Rounded grains clearly the result of melt-freeze cycling
- c Clustered grains

Grain size (D) in millimetres

Free water content (W)
- D Dry
- M Moist
- W Wet
- VW Very wet

Upper boundary

Lower boundary



WEATHER OBSERVATIONS

Sky conditions
- Clear
- Scattered cloud
- Broken cloud
- Overcast
- Obscured

Precipitation
- NIL No precipitation
- VL★ Very light snow
- L★ Light snow
- M★ Moderate snow
- H★ Heavy snow

Wind

9 NOVEMBER — Weather: NIL CALM

16 NOVEMBER — Weather: VL★ CALM

23 NOVEMBER — Weather: NIL CALM

30 NOVEMBER — Weather: VL★ CALM

7 DECEMBER — Weather: VL★ LIGHT

14 DECEMBER — Weather: NIL N, LIGHT

21 DECEMBER — Weather: M★ S, LIGHT

28 DECEMBER — Weather: L★ CALM

4 JANUARY — Weather: VL★ W, LIGHT

11 — Weather: NIL

20F

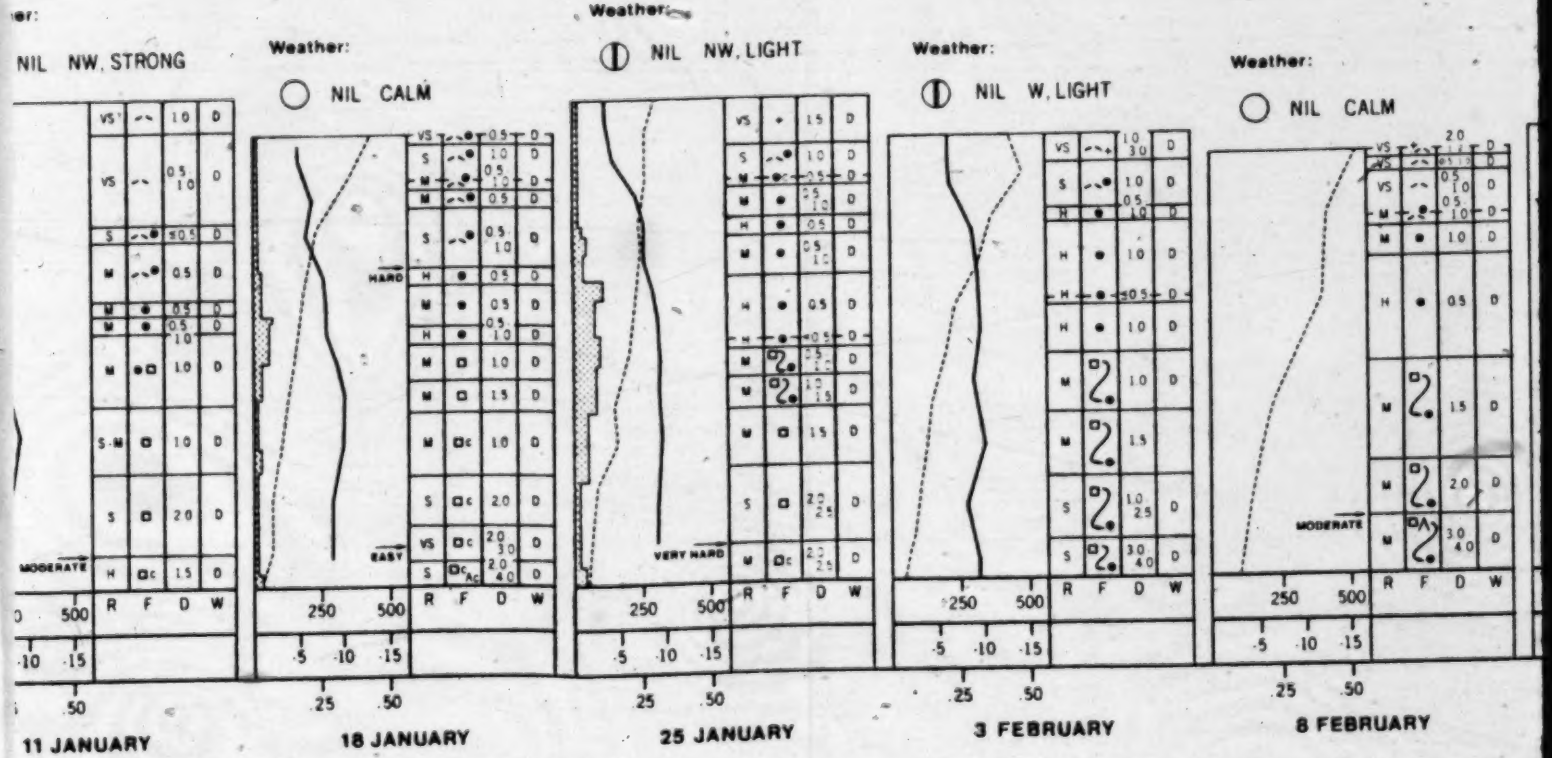
Wind

CALM 0 m s^{-1}

LIGHT 0-7 m s^{-1}

MODERATE 8-11 m s^{-1}

STRONG >11 m s^{-1}



3 of 3

Depth hoar layer (cm)

Snowpack depth (cm)

Ram number (Newtons)

Temperature (°C)

Specific gravity

8 FEBRUARY
Weather: NIL CALM

24 FEBRUARY
Weather: NIL CALM

10 MARCH
Weather: VL★ S. LIGHT

25 MARCH
Weather: NIL CALM

5 APRIL
Weather: NIL CALM

12 APRIL
Weather: NIL CALM

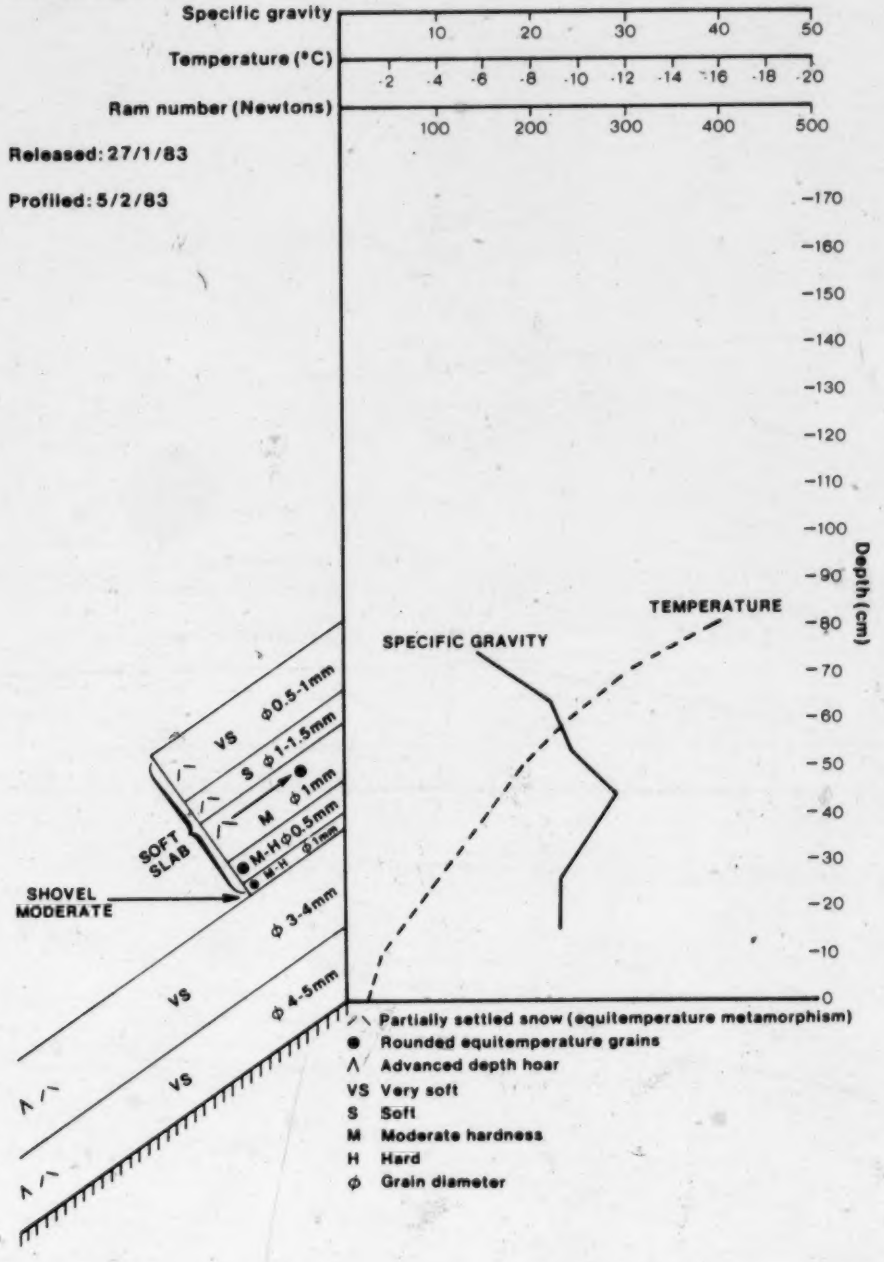
18 APRIL
Weather: NIL NW, MODERATE

3 MAY
Weather: H★ CALM

17 MAY

APPENDIX 3: FRACTURE LINE PROFILES; FORTRESS MOUNTAIN AND HIGHWOOD PASS, 1982-83

Mt. Inflexible No. 3



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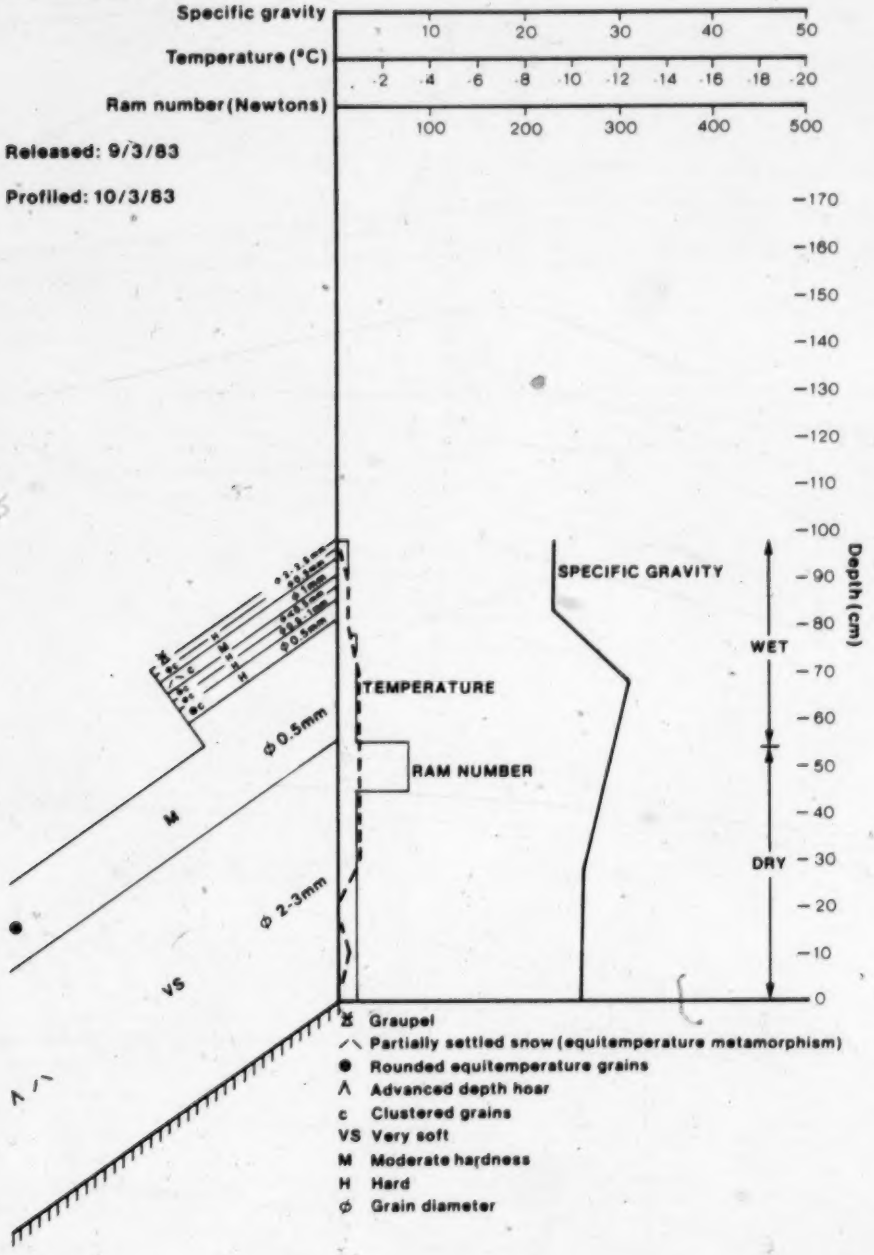

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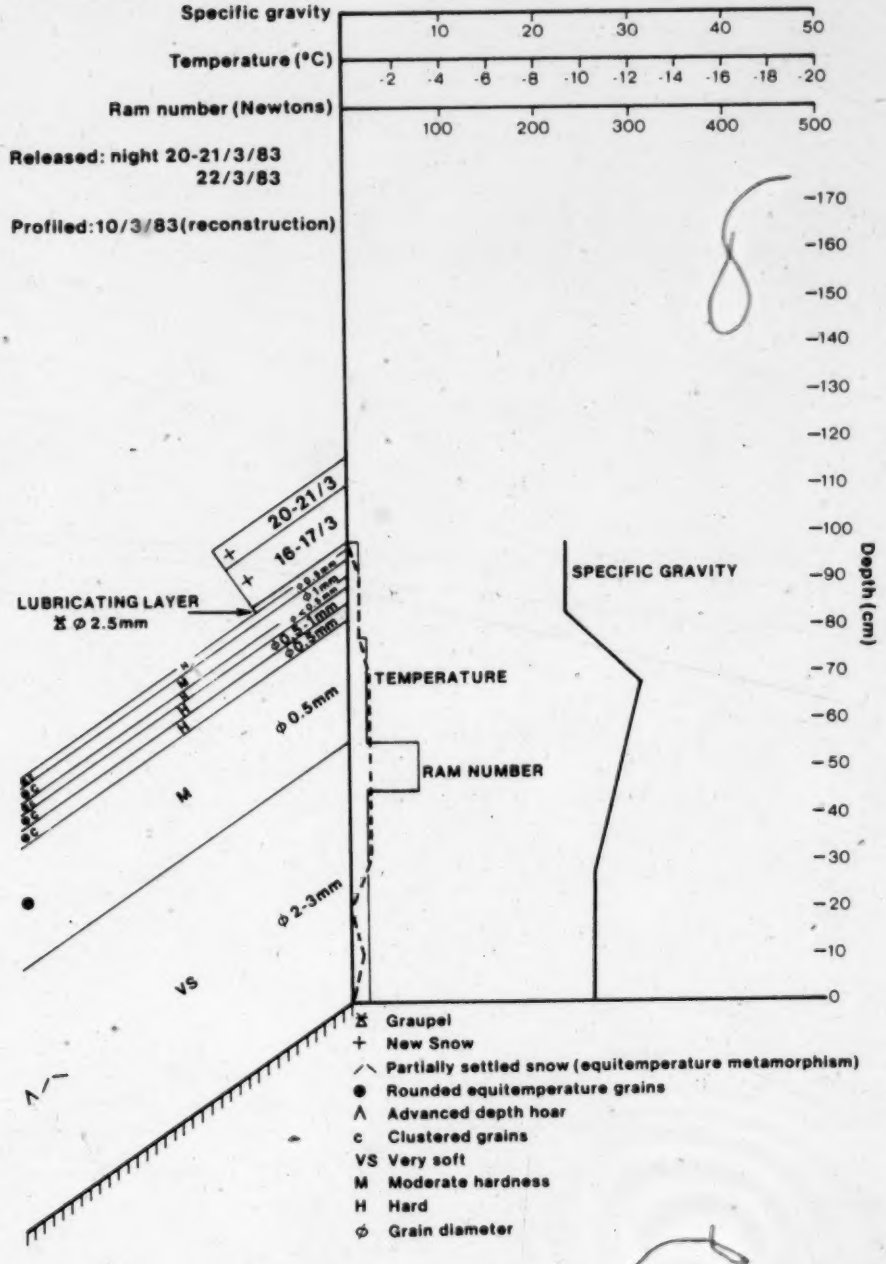

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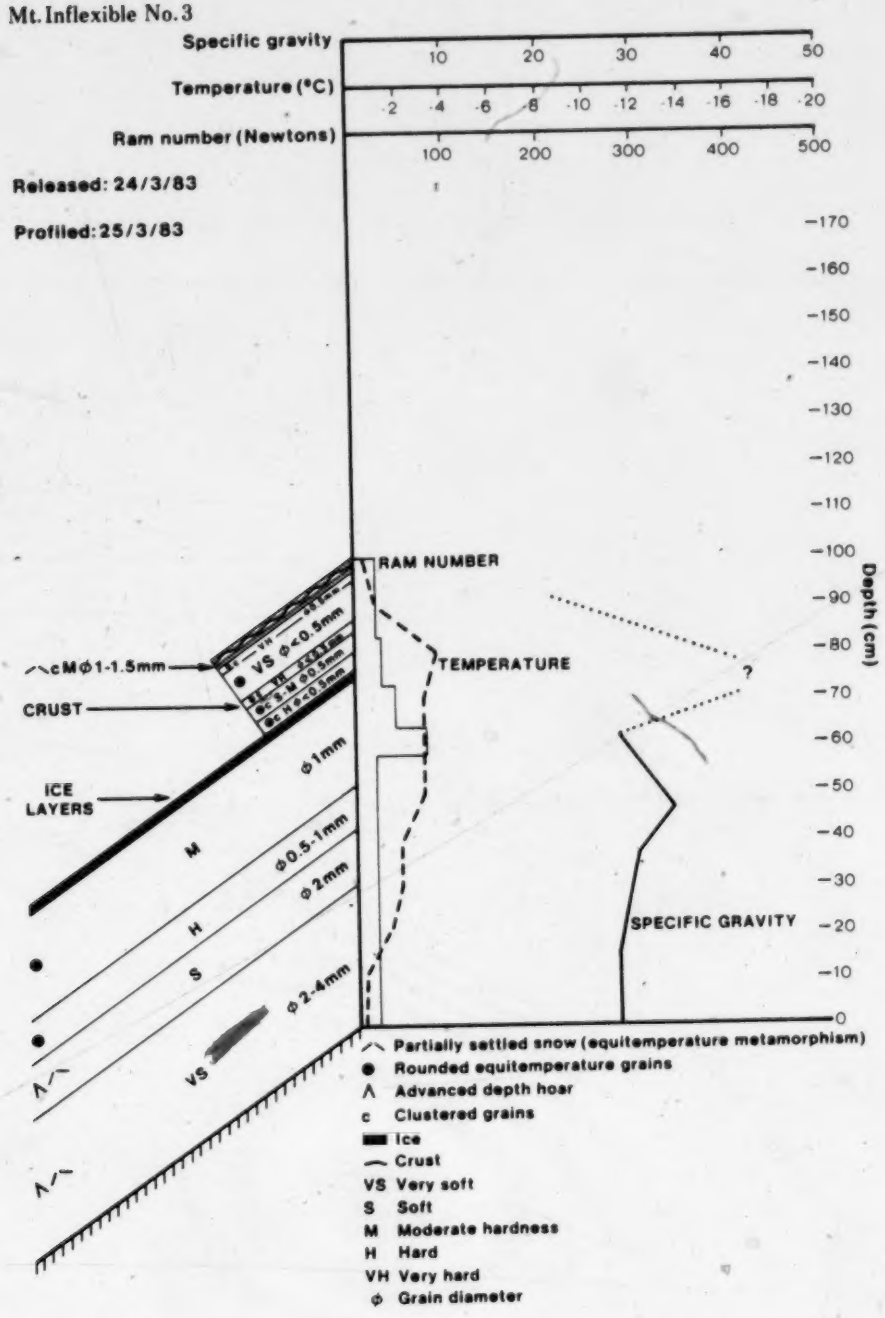

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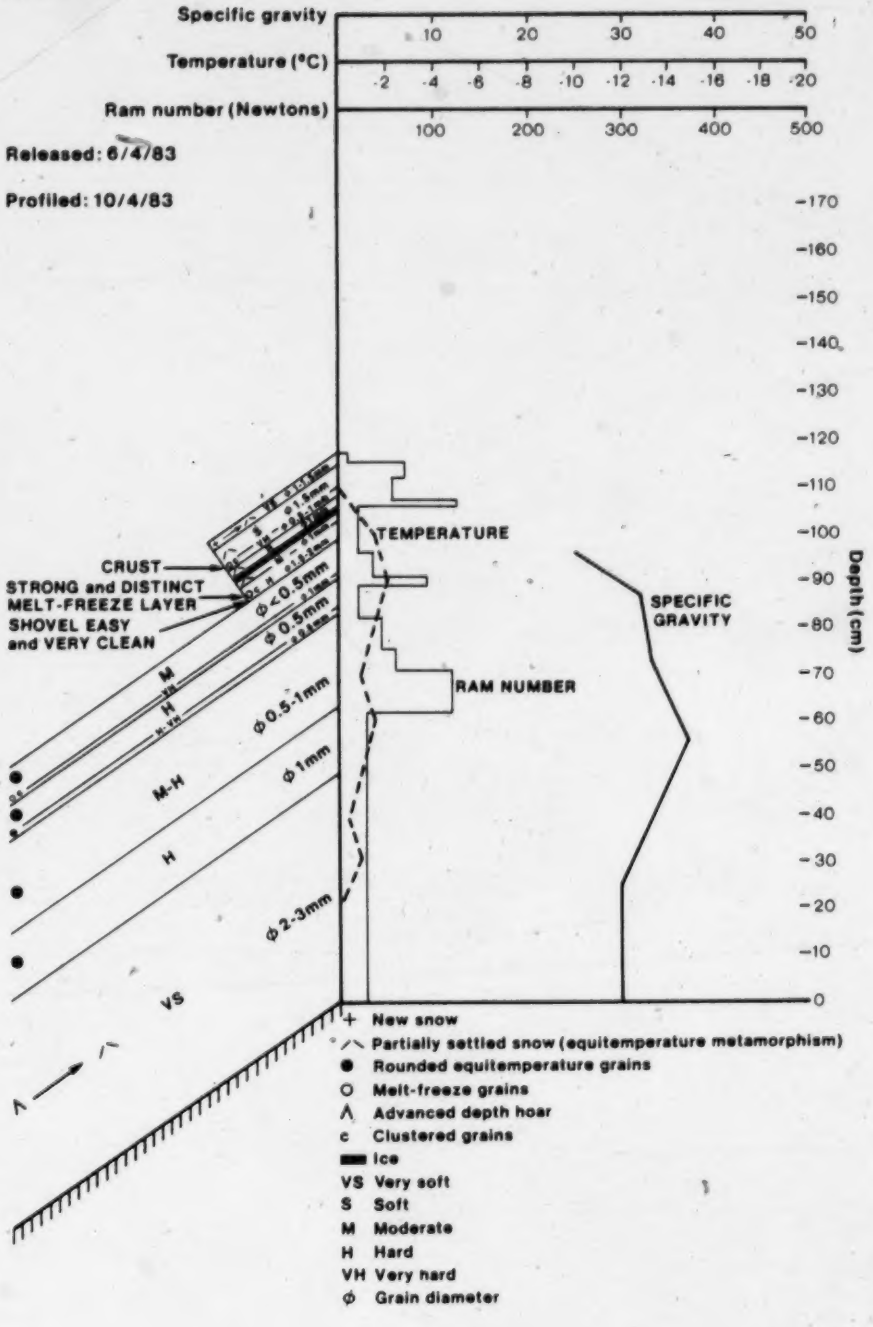

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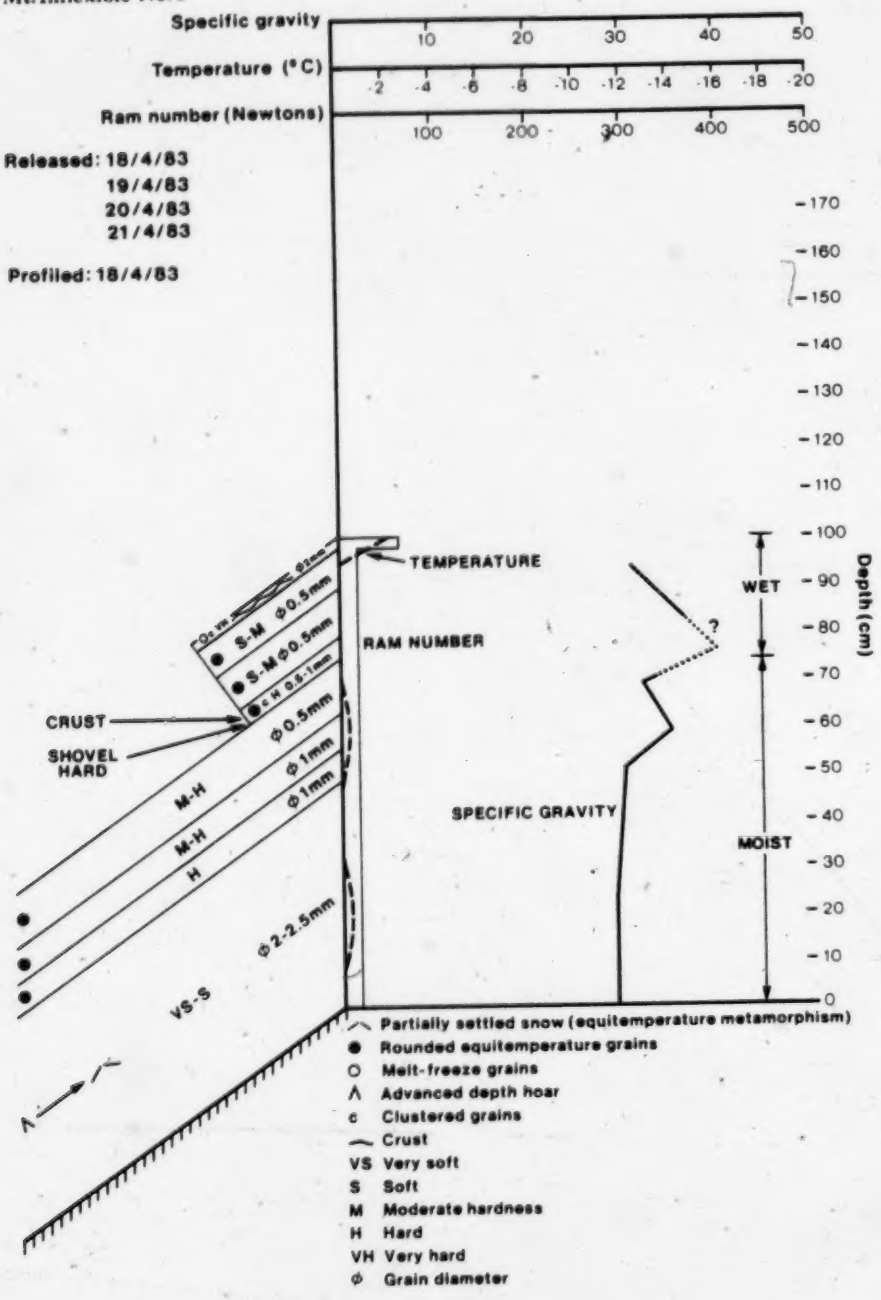

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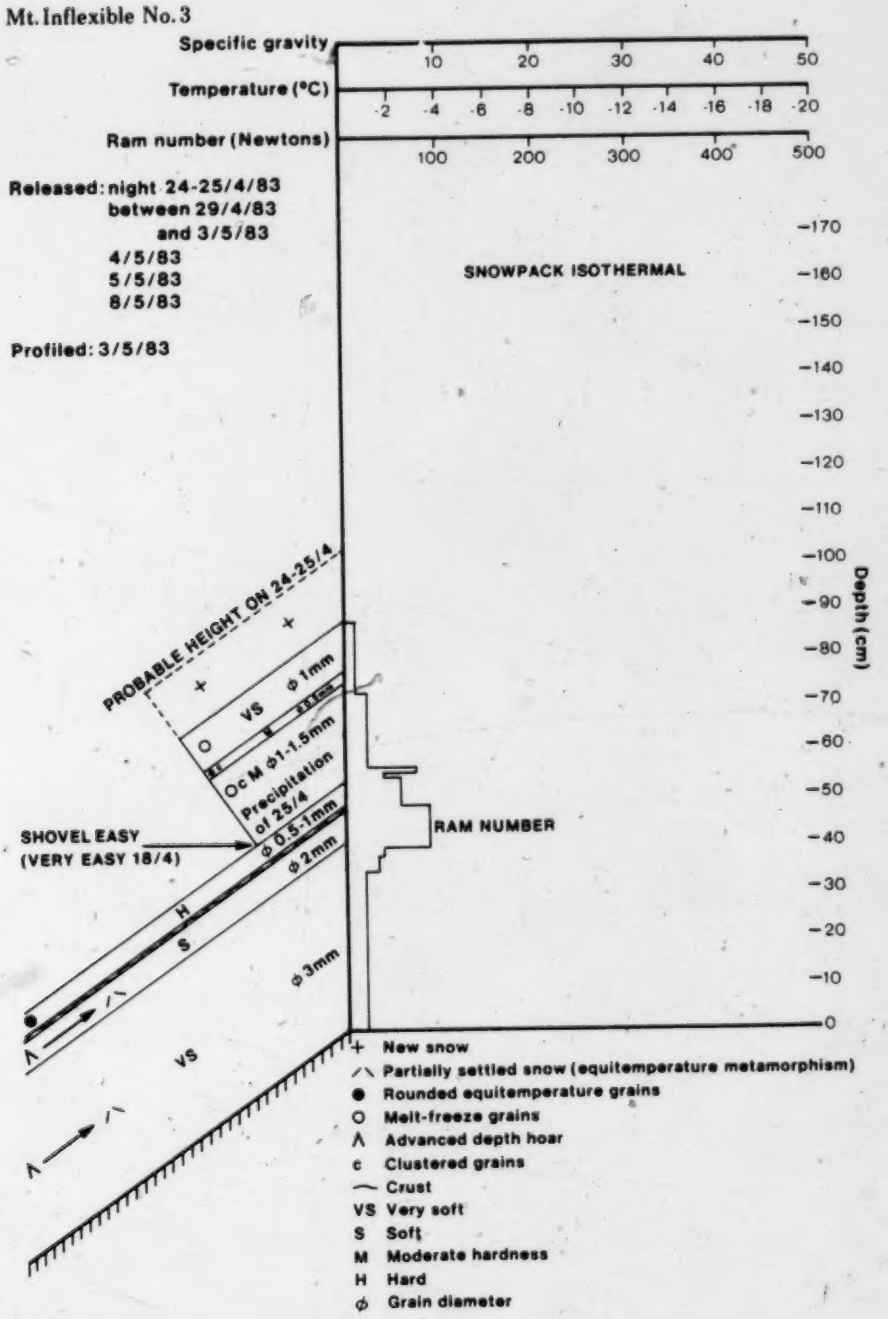

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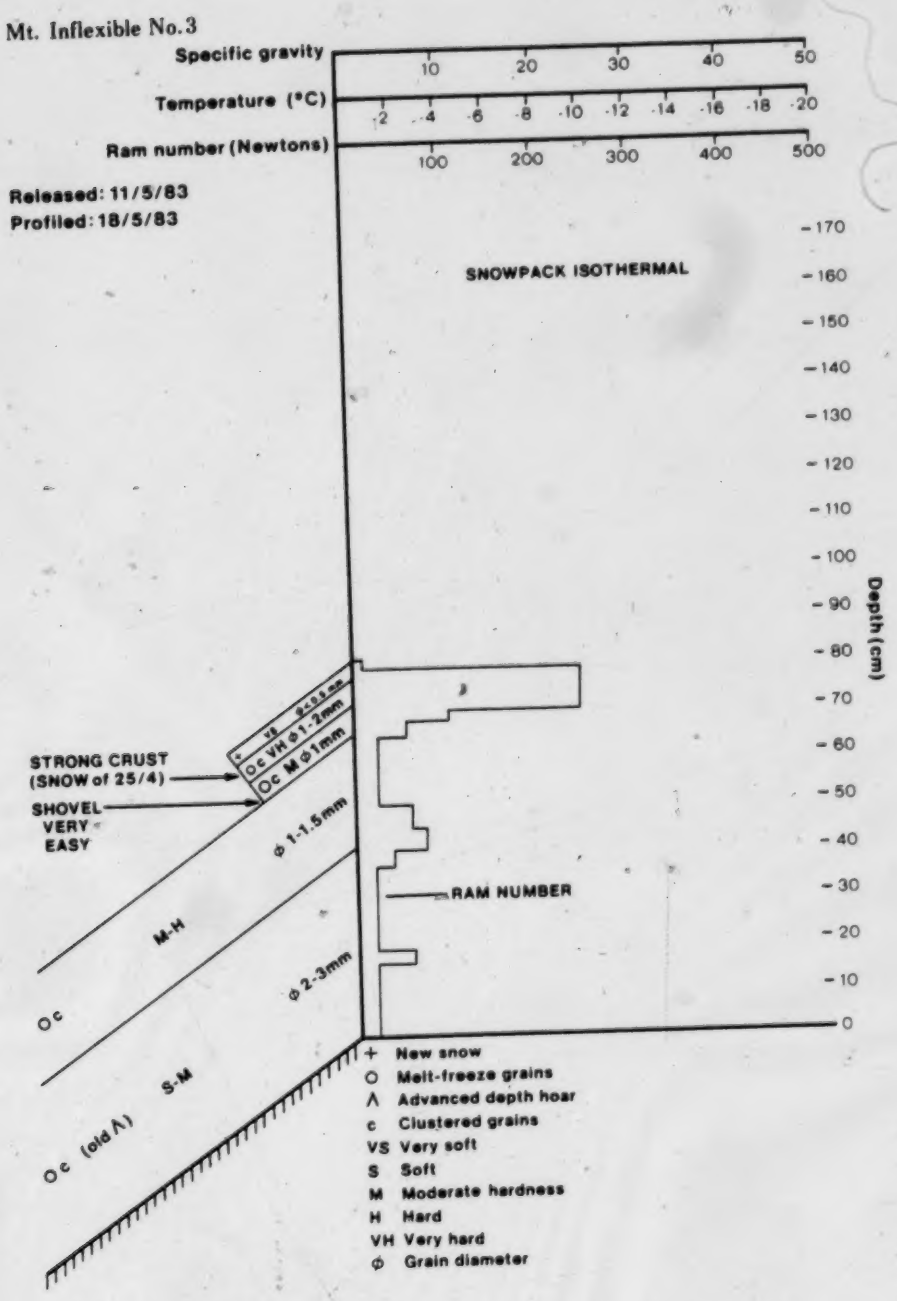
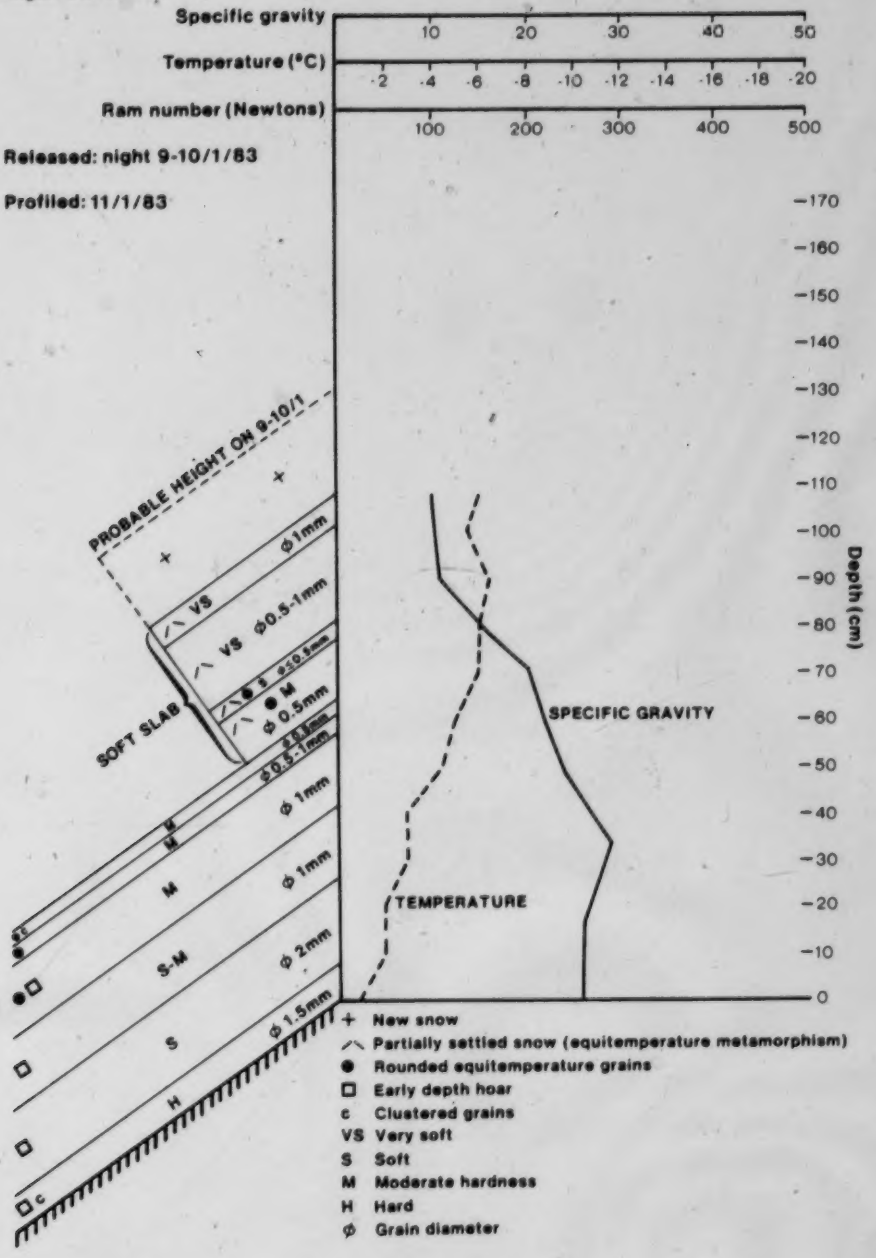
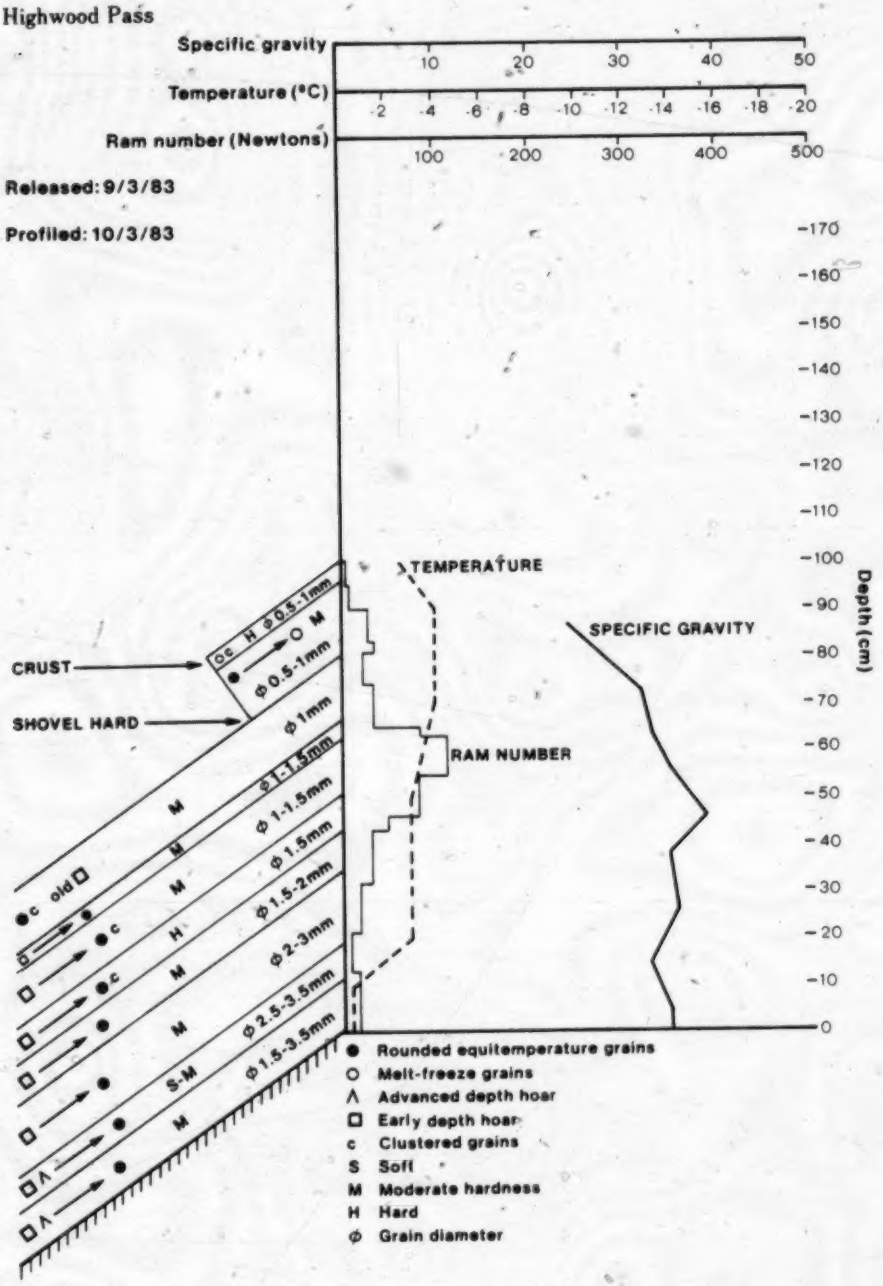
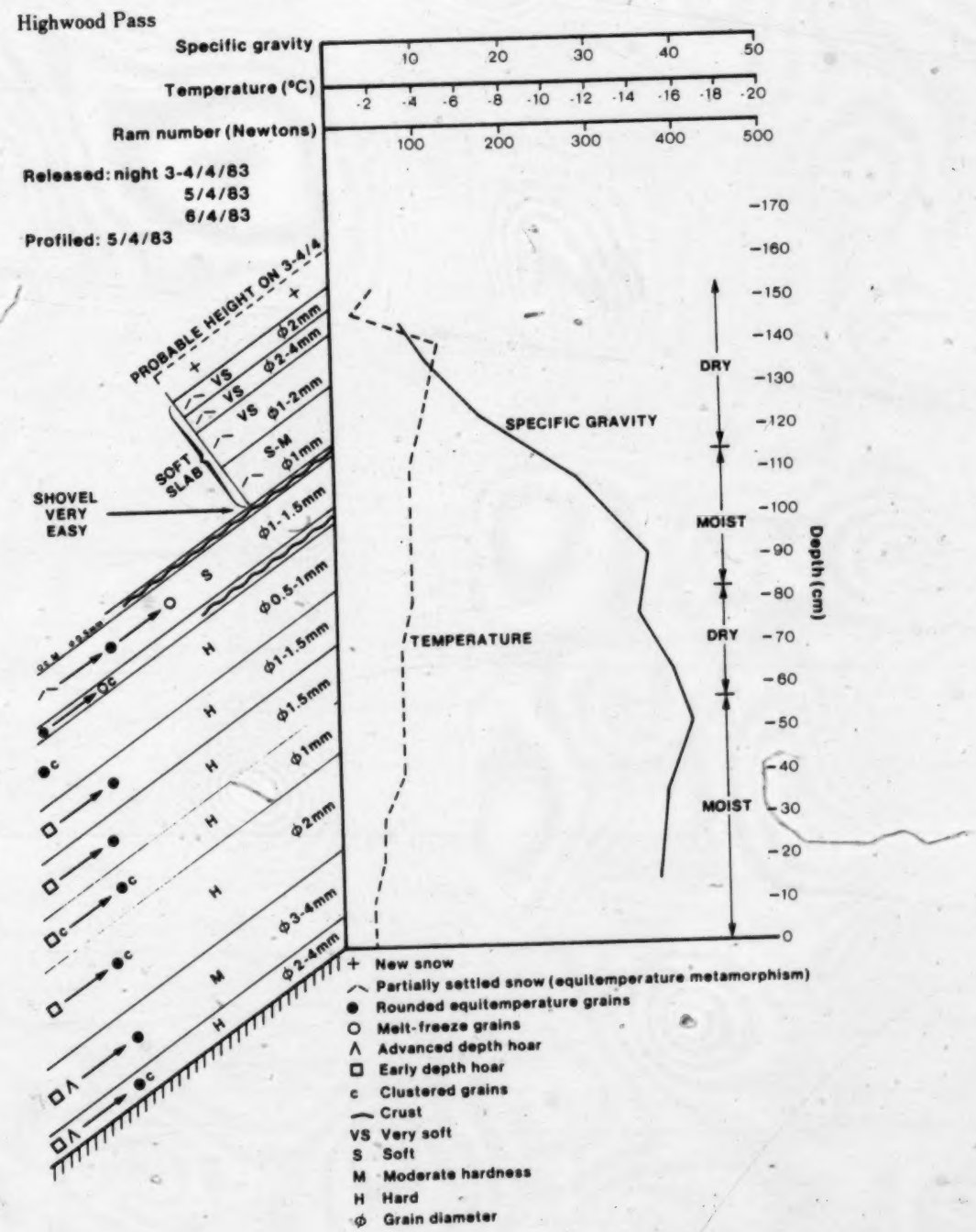


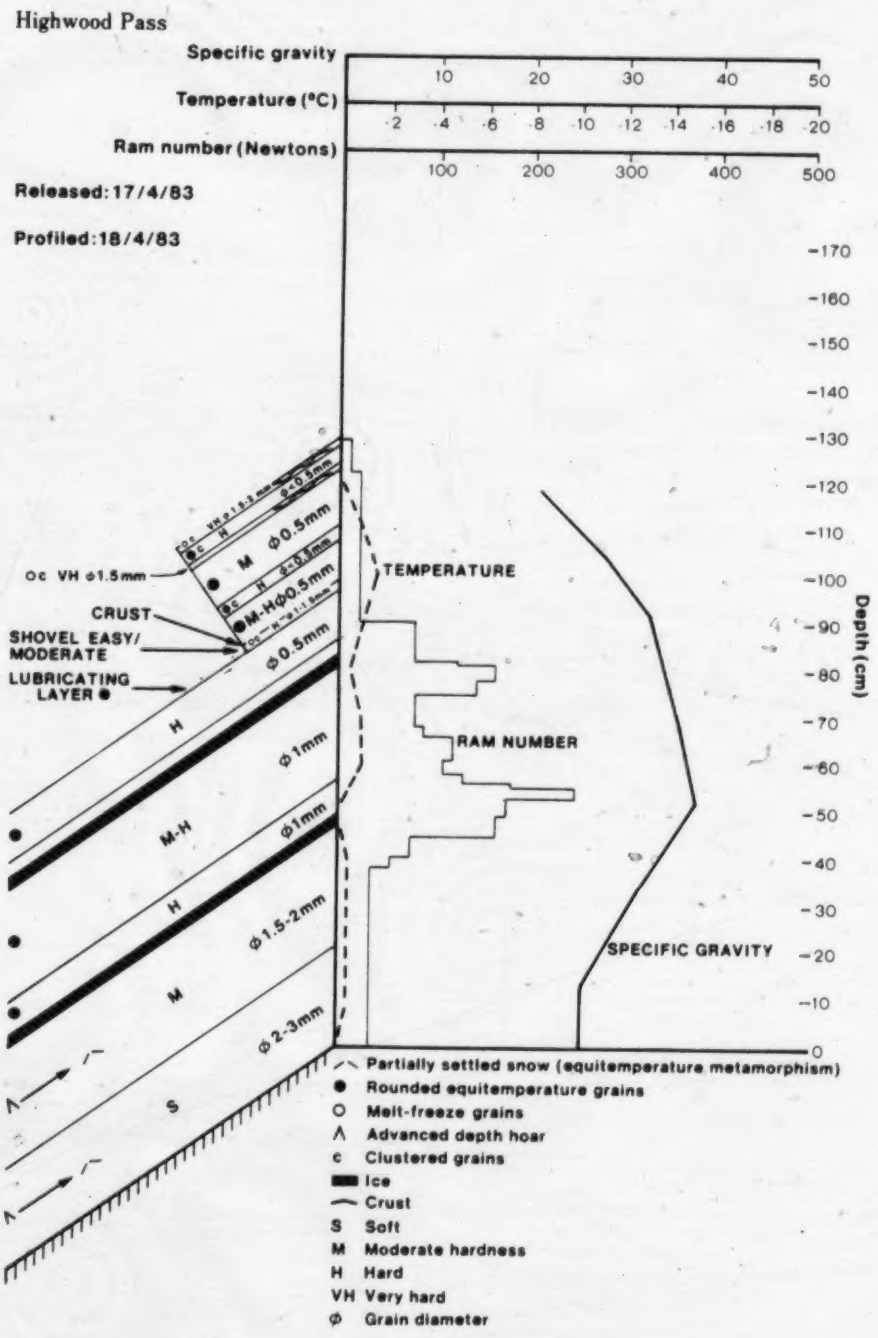
Highwood Pass



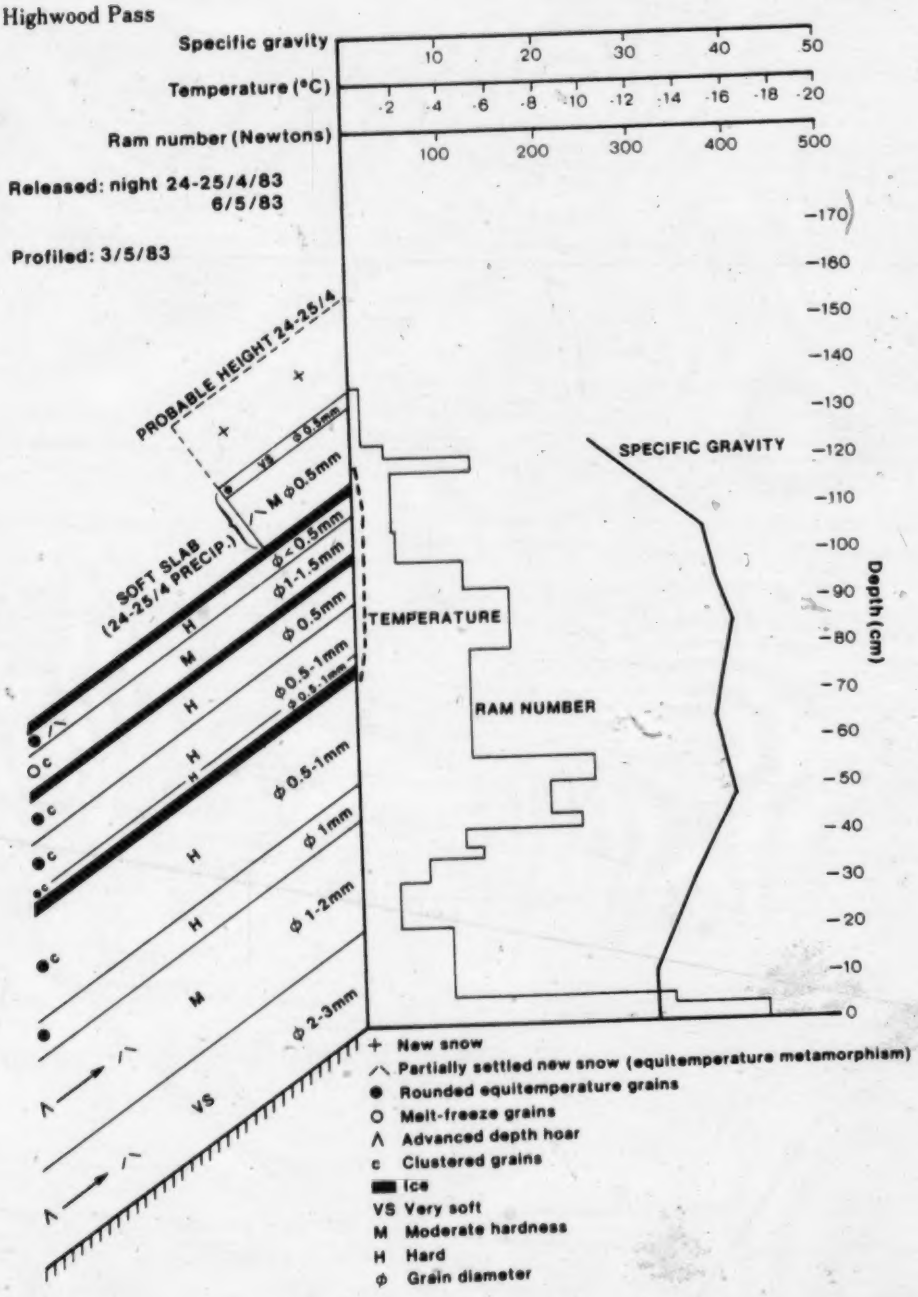
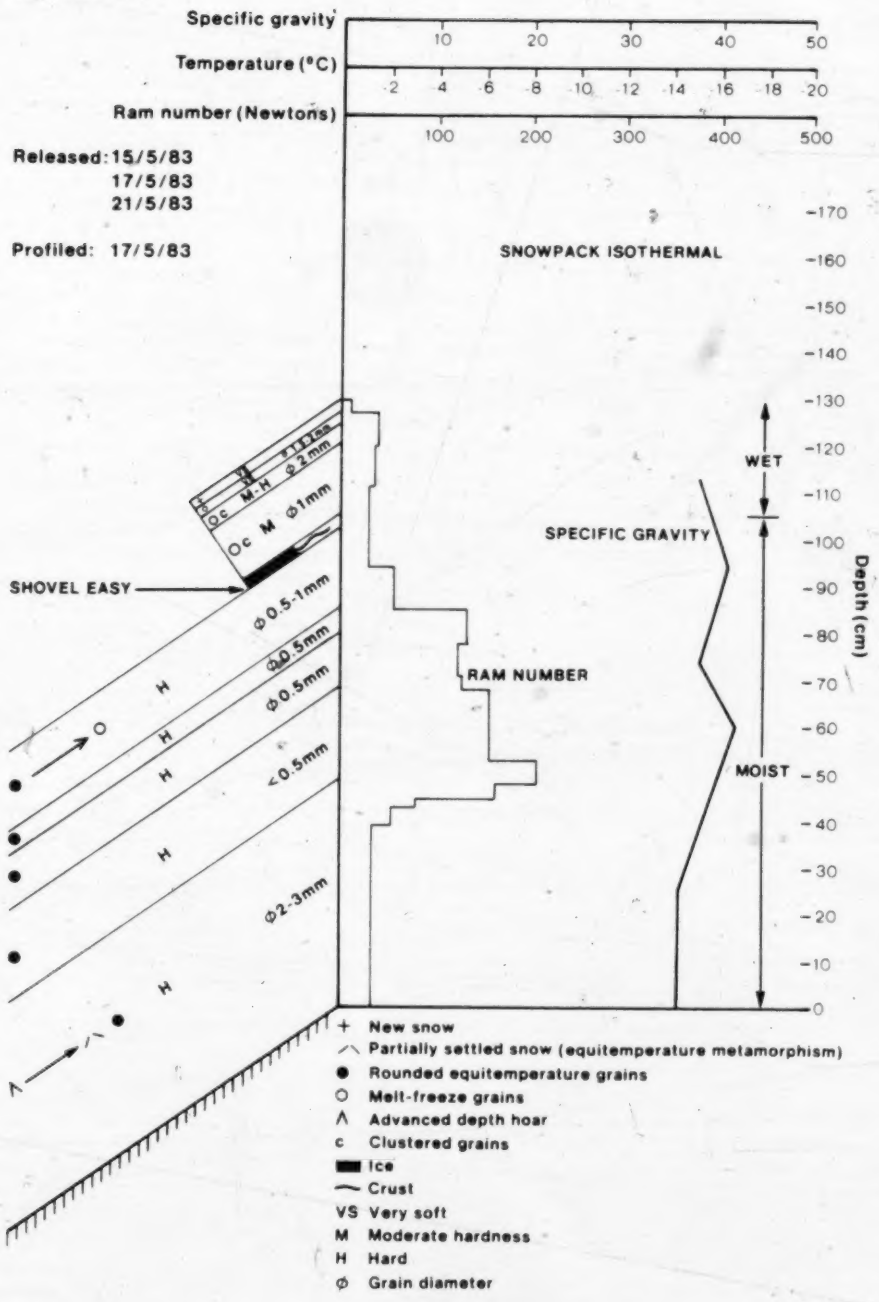
Highwood Pass




Highwood Pass
Specific gravity
10 20 30 40 50
Temperature (°C)
-2 -4 -6 -8 -10 -12 -14 -16 -18 -20
Ram number (Newtons)
100 200 300 400 500
Released: night 3-4/4/83
5/4/83
6/4/83
Profiled: 5/4/83
PROBABLE HEIGHT ON 3-4/4
SOFT SLAB
SHOVEL VERY EASY
SPECIFIC GRAVITY
TEMPERATURE
DRY
MOIST
DRY
MOIST
Depth (cm)
+ New snow
Partially settled snow (equitemperature metamorphism)
Rounded equitemperature grains
Melt-freeze grains
Advanced depth hoar
Early depth hoar
c Clustered grains
Crust
VS Very soft
S Soft
M Moderate hardness
H Hard
ϕ Grain diameter


Highwood Pass
Specific gravity
Temperature (°C)
Ram number (Newtons)
Released: 17/4/83
Profiled: 18/4/83
10 20 30 40 50
-2 -4 -6 -8 -10 -12 -14 -16 -18 -20
100 200 300 400 500
-170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0
Depth (cm)
TEMPERATURE
RAM NUMBER
SPECIFIC GRAVITY
Oc VH ϕ1.5mm
CRUST
SHOVEL EASY/ MODERATE
LUBRICATING LAYER
M ϕ0.5mm
M-H ϕ0.5mm
ϕ0.5mm
H
ϕ1mm
M-H
ϕ1mm
H
ϕ1.5-2mm
M
ϕ2-3mm
S
Partially settled snow (equitemperature metamorphism)
Rounded equitemperature grains
Melt-freeze grains
Advanced depth hoar
c Clustered grains
Ice
Crust
S Soft
M Moderate hardness
H Hard
VH Very hard
ϕ Grain diameter

Highwood Pass



Highwood Pass